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Report No. CG-D-04-89

AD-A208 201

ENVIRONMENTAL ATLAS OF THE BERING SEA

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FINAL REPORT
OCTOBER 1988

Prepared for:

U.S. Coast Guard
Research and Development Center
Avery Point
Groton, CT 06340-6096

and

U.S. Department Of Transportation
United States Coast Guard
Office of Engineering and Development
Washington, DC 20593-0001

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Technical Report Documentation Page

1. Report No. CG-D-04-89	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ENVIRONMENTAL ATLAS OF THE BERING SEA		5. Report Date OCTOBER 1988
		6. Performing Organization Code
7. Author(s) A.L. Comiskey and J.E. Ostrom		8. Performing Organization Report No. R&DC 21/88
9. Performing Organization Name and Address Northern Technical Services, Inc. 750 West 2nd Avenue, Suite 100 Anchorage, Alaska 99501		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTCG39-87-R-80500
12. Sponsoring Agency Name and Address U.S. Coast Guard Research and Development Center Avery Point Groton, Connecticut 06340-6096	Department of Transportation U.S. Coast Guard Office of Engineering and Development Washington, D.C. 20593-0001	13. Type of Report and Period Covered FINAL
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This atlas contains oceanographic, meteorologic, and air-sea interface information. The information is a composite of traditional climatological and oceanographic data interspersed with non-traditional empirical information useful to Coast Guard operations. Some unique subjects are discussed such as ship operations in first year ice and flying conditions over water. The atlas is also unique in that subjects are discussed both briefly (first portion of atlas) and extensively (second portion) to accommodate readers with different levels of interest.

17. Key Words Bering Sea Atlas Oil Spills Sea Ice Superstructure ice Alaska Meteorology Alaska Oceanography	18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report) UNCLASSIFIED	20. SECURITY CLASSIF. (of this page) UNCLASSIFIED	21. No. of Pages	22. Price

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METRIC CONVERSION FACTORS

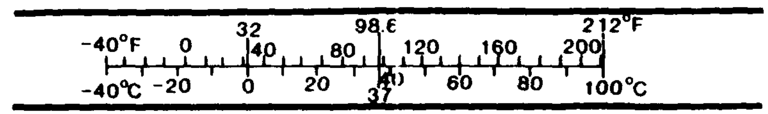
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25. SD Catalog No. C13.10:286

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 <u>INTRODUCTION</u>

In this atlas of the Bering Sea, oceanic, atmospheric, and oceanic-atmospheric interface information is assembled for the purpose of supporting all U.S. Coast Guard operational activities including maximizing the effectiveness of oil spill related activities. These activities include pre-spill planning as well as post-spill mitigation activities. Every oceanic-atmospheric subject that might affect oil spill trajectories or resources at risk to any significant degree is discussed. The latest "state-of-the-art" as determined by our studies is included in the atlas except esoteric material which is beyond the scope of this atlas.

The atlas is organized and designed to accommodate two basic levels of readers, or two basic types of readers. The two <u>levels</u> of readers are 1) those requiring mostly general information; and 2) those requiring in-depth information. Sections 2.0 through 4.0 contain brief discussions of some subjects and summaries of other subjects which are discussed in depth elsewhere in the atlas. When the subject is a summarization, the reader is referred to the appropriate section which contains the related in-depth discussion.

The in-depth discussions occur in Sections 5.0 through 8.0 or in the appendices. For example, a summary of tides is given in 2.4 with an in-depth discussion in 5.2. The format is designed to make an overview, or summary, easily available to the reader with the provision for easily accessible in-depth discussions elsewhere if needed. In short, the overview material occurs in the first sections and the in-depth material occurs in the latter sections. When the subject is summarized in the first sections, it is so indicated in the Table of Contents in addition to a specific reference in the summarized section to the in-depth discussion which occurs later in the text. The authors feel that the above will provide maximum ease of readability for the different types of readers.

The atlas of the Bering Sea is similar in many respects to other atlases developed for more southern areas. The major differences are the presence of considerable sea ice during the winter months as well as possible severe superstructure icing on marine structures. Relatively cold ocean water can seriously affect aircraft flying conditions for extended periods during the summer months. These subjects are discussed in depth. Figure 1.0-1 depicts the Bering Sea Atlas area and points or areas for reference.

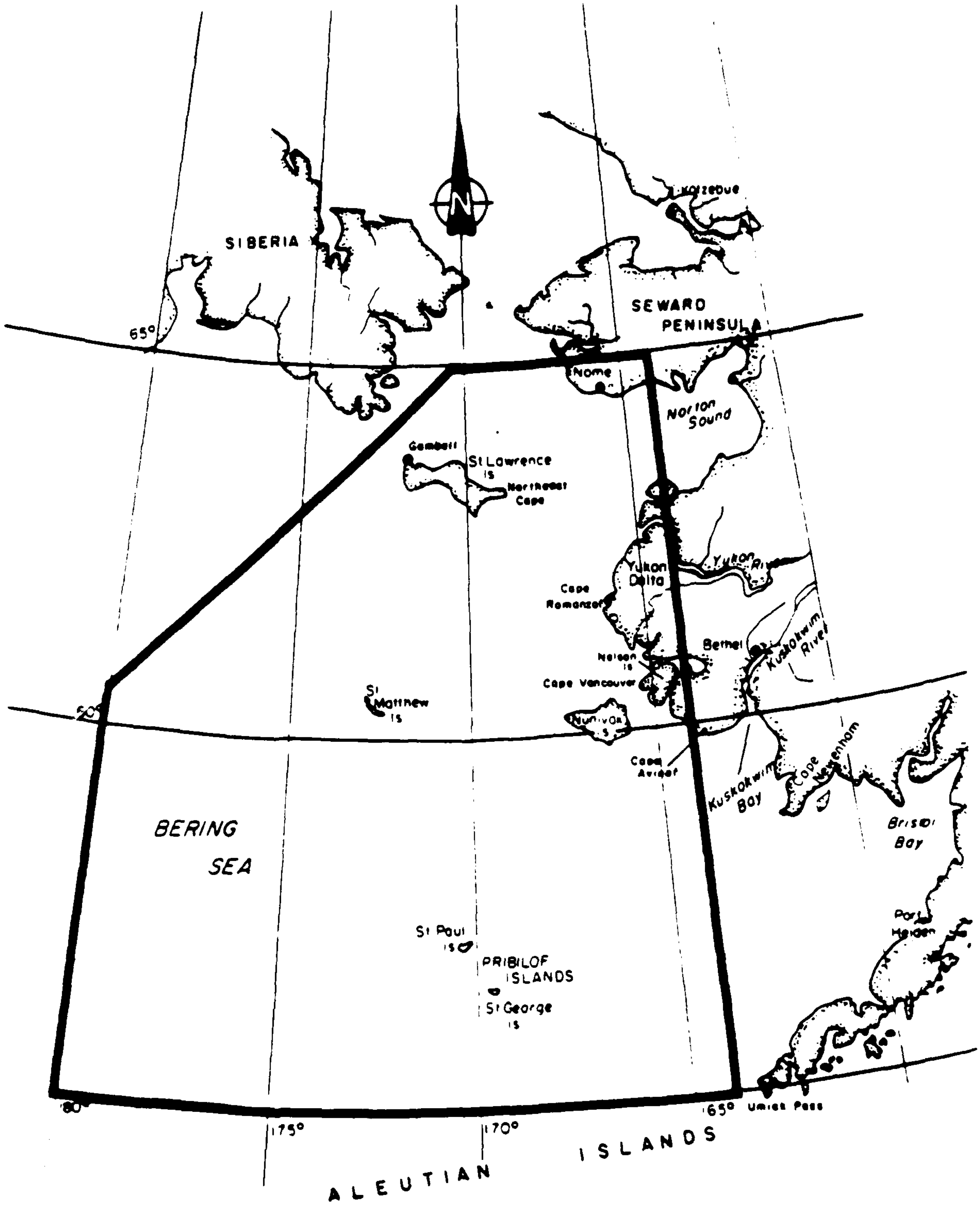

Figure 1.0-1. Bering Sea Atlas area and prominent geographic and oceanographic features.

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2.0 PHYSICAL GEOGRAPHY

The area of interest along with the resource development areas are shown in figure 2.0-1. The physical features are discussed separately as follows.

2.1 Topography

The coastlines of the mainland and nearby islands are much more irregular or convoluted than might be expected when viewing Figure 1.0-1. The coastline shown on NOS NOAA Chart 16006-Bering Sea Eastern Part (Figure 2.1-1) is more representative of the actual coastline. Landmarks are essentially non-existent along much of the coastline because of extremely low lying land. However, there are a few recognizable and navigationally useful areas of higher terrain.

The most notable are Cape Vancouver and Cape Romanzoff. Cape Vancouver marks the western extremity of Nelson Island which has significant topographic relief from Cape Vancouver northeastward; however, the "island" is embedded in the mainland area and only a small percentage of its relatively high terrain lies along the outer coast.

Relatively high terrain extends eastward for approximately 40 nmi from Cape Romanzoff. Thus navigation in bays immediately to the north and south is facilitated by the identifiable high terrain. Nevertheless, navigation in the bays is not easy because of the offshore low-lying barrier island and shoals.

Unfortunately, the National Ocean Survey (NOS) charts do not provide a high resolution of land features and it is advisable to have U.S. Geological Survey (USGS) quadrangle charts (scale 1:250,000) available along with the NOS charts for close in navigation both by water bourne equipment as well as aircraft.

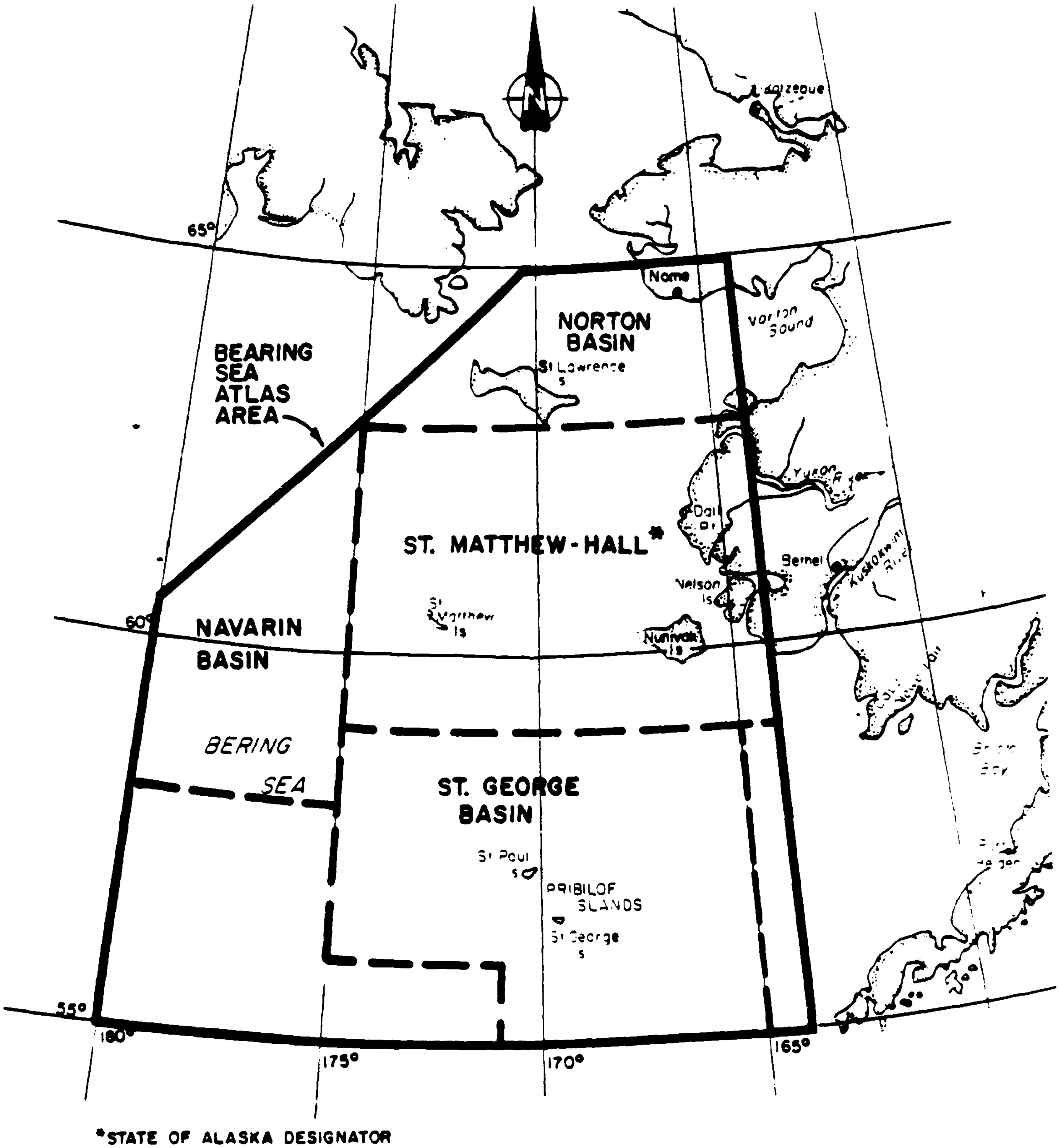


Figure 2.0-1. The Bering Sea Atlas area and designated resource areas within the atlas area are shown.

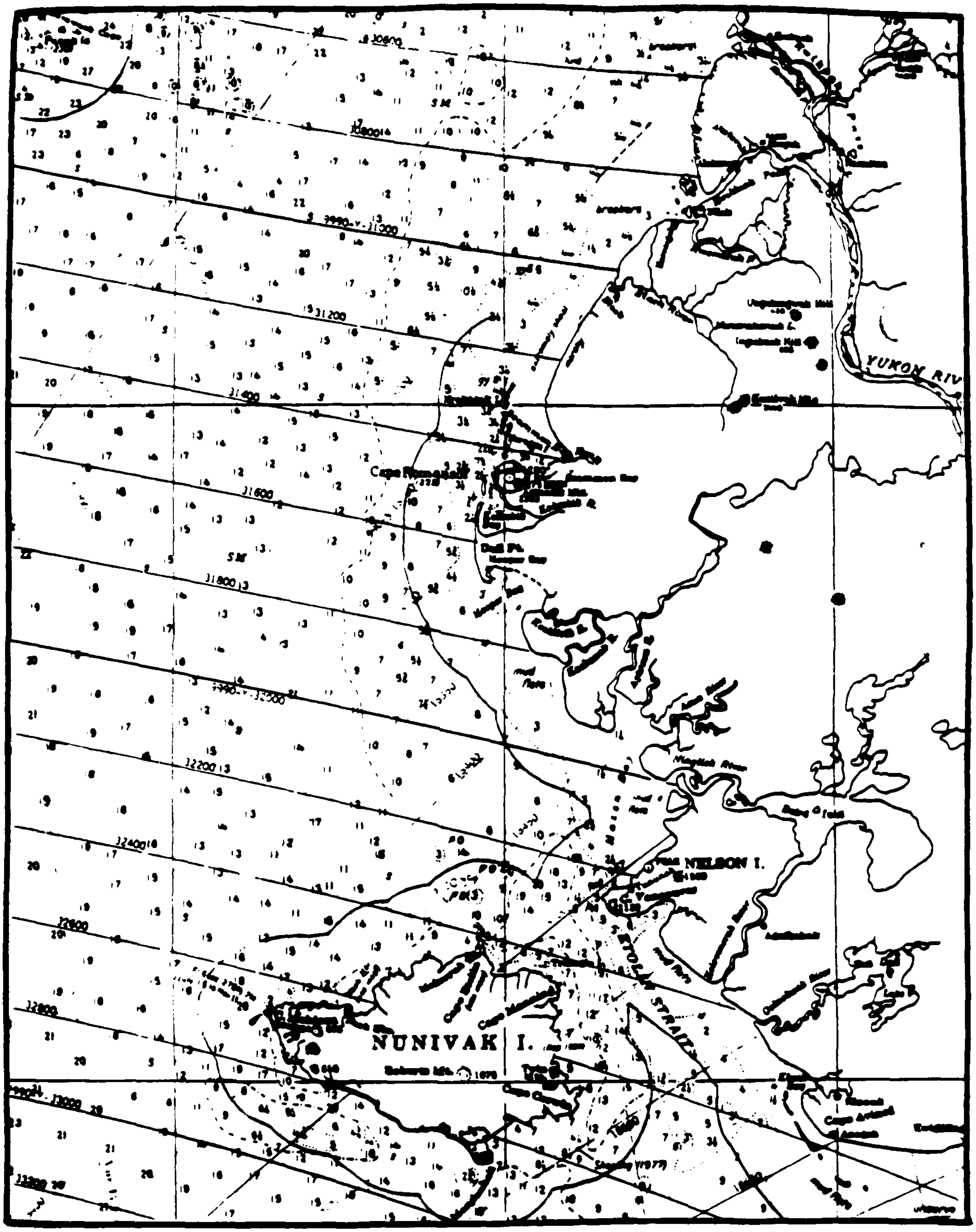


Figure 2.1-1. The Alaska coastline as depicted by NOS NOAA Chart 16006 - Scale 1:1,534,076.

The quadrangle charts suggested are: Kuskokwim Bay, Baird Inlet, Nunivak Island, Hooper Bay, Black, Kwiguk, and St. Michael. The offshore islands of Nunivak, St. Lawrence, St. Matthew, and the Pribilofs generally have more definite terrain features and the quadrangle charts for those areas are not as necessary for navigation as along the mainland coast.

2.2 Bathymetry

The outstanding feature of the Bering Sea is its large continental shelf area which extends westward and southwestward 300 - 500 nmi from the Alaska mainland (Figure 2.2-1). Of particular interest is the precipitous change in water depth from 140 m to 2000 m over relatively short horizontal distances. Alaska has about 74 percent of the U.S. Continental Shelf area (Rosenburg, et. al., 1980) and much of the 74 percent is in the Bering Sea. Physical considerations are that continental shelves are conducive to storm surges (see Section 6.7) and the relatively shallow water may affect wind wave shapes which in turn may influence modelers and forecasters to select one wave spectra over another. For storm surge affects and wind wave affects see Sections 6.7 and 5.3 respectively.

2.3 General Circulation

The general circulation of the Bering Sea is as depicted in Figures 2.3-1 and 2.3-2 (Leslie, 1987). General circulation is an integral part of the physical geography of the Bering Sea. However, its value as an oil spill trajectory parameter is questionable. General circulation as depicted is an estimate of long term (years) net flow in the water column. The prime driving force is the wind. Because the wind is highly variable from week to week, month to month, and even year to year, the short term wind induced currents very frequently override the general circulation pattern. Diurnal and semi-diurnal lunar tides also override the general circulation as well as affecting

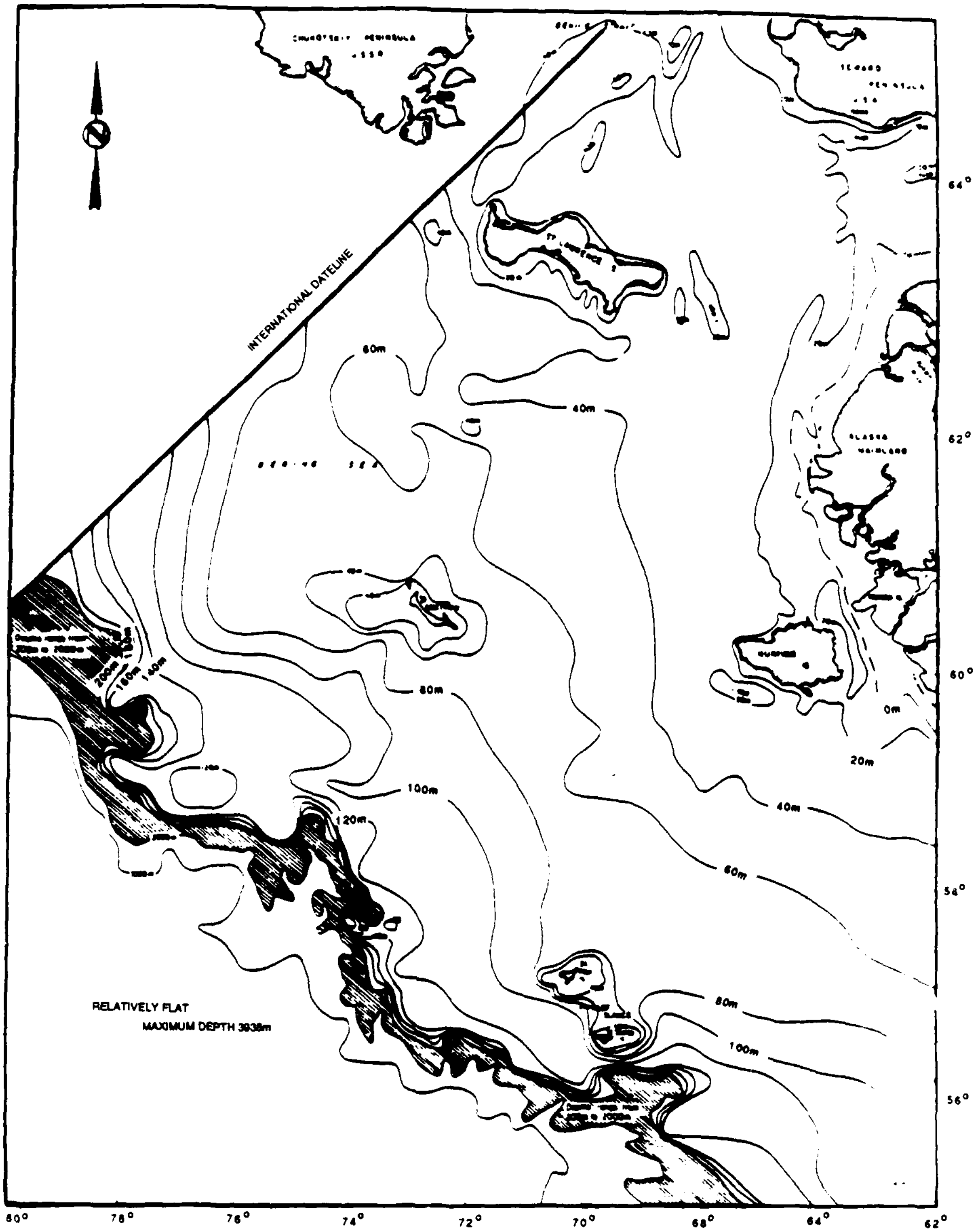


Figure 2.2-1. The isobaths depicts the gradual scope of the continental shelf from the shoreline to about 140 m. Beyond 140 m the increase in depth is precipitous to 1,500 or 2,000 m. The shaded area depicts water depths from 200 to 2,000 m. Oceans slopes above and below those depths are generally slight. Isobaths are derived from NOAA Charts 513, 514, and 16,006.

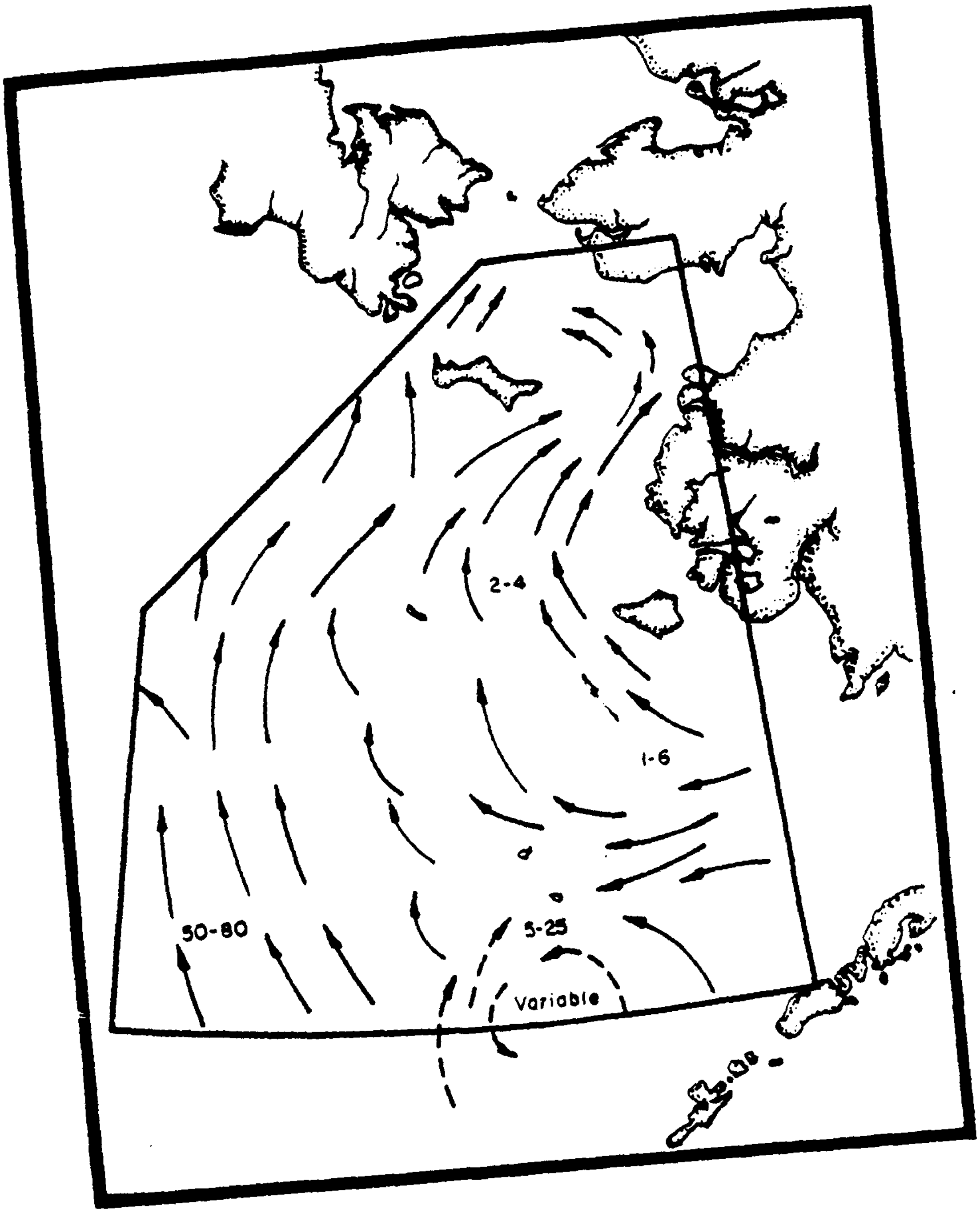


Figure 2.3-1. Estimated Bering Sea summer currents (Leslie, 1987) speeds in cm/sec.

Figure 2.3-2. Estimated Bering Sea winter currents (Leslie, 1987) speeds in cm/sec.

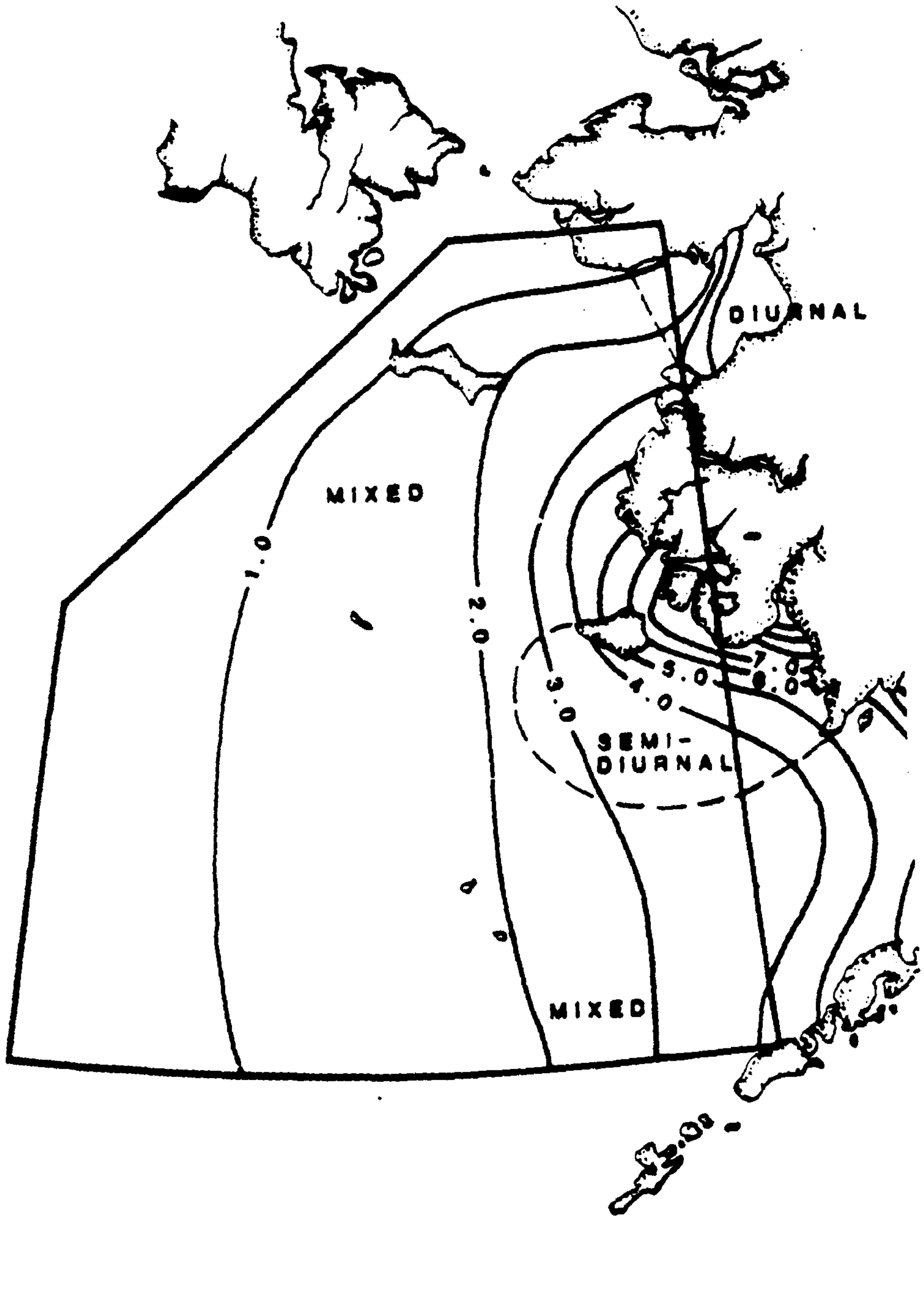


Figure 2.4-1. Cotidal lines of Greenwich high water interval (in hours) and areas of semi-diurnal, diurnal, and mixed daily tidal occurrences. (Pawlowski, R., 1986)

Figure 2.4-2. Estimated corange lines (in feet).
(Pawlowski, R., 1986)

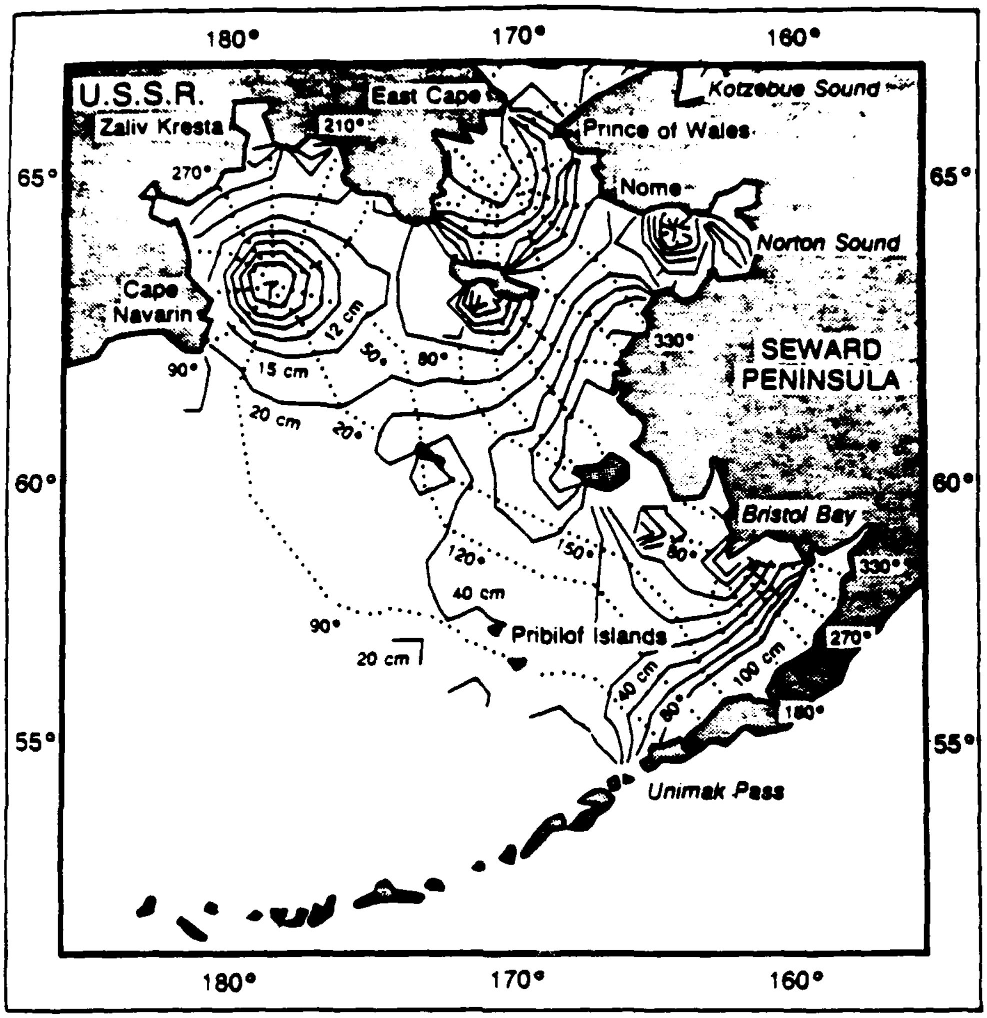


Figure 2.4-3. Computed tidal corange lines for the semidiurnal tidal component using a three dimensional model of the Bering and Chukchi seas. (Liu, S.-K. 1981)

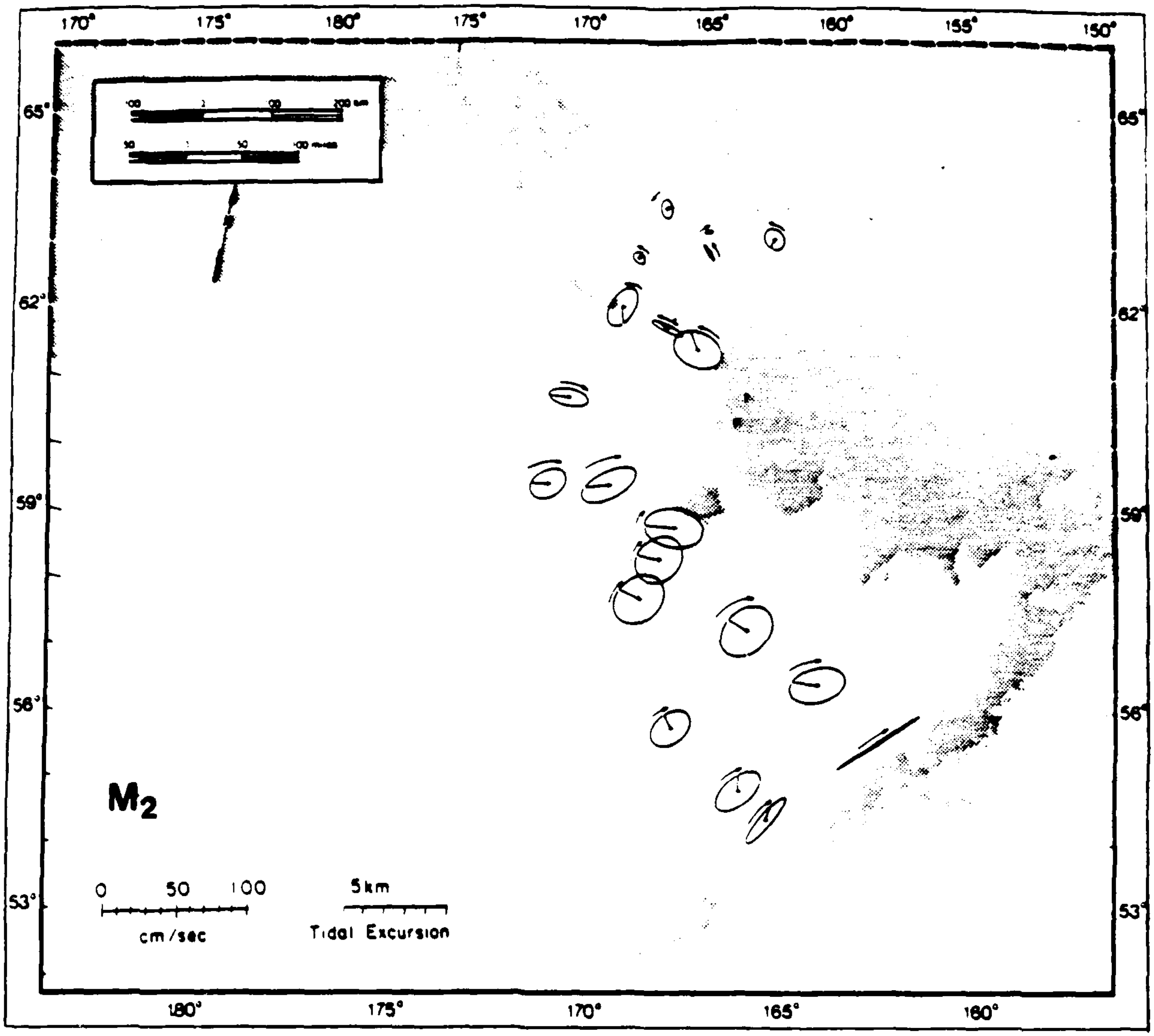


Figure 2.4-4. Tidal current ellipses for the M_2 constituent. (Pearson et al., 1980)

the short term wind currents. With both the wind and tides overriding the general circulation pattern, it is advisable that general circulation not be used for oil spill trajectory forecasts except for very special applications or in discrete areas where general circulation currents are known to be strong and persistent. Most general circulation currents are weak (5-15 cm/sec) (Kinder and Schumacher, 1981). General circulation is discussed further in Section 5.2.1.

2.4 Tides

Currents in the Bering Sea have average speeds of less than 50 cm/sec except along some coasts and in or out of bays along the Alaska mainland. The tides may be semi-diurnal, diurnal, or mixed (Figure 2.4-1). Measured range is from 1 ft (0.3 m) to nearly 8 ft (2.44 m). See Figure 2.4-4 for tidal current ellipses. The tidal wave (lunar) generally moves from southwest to northeast. See Section 3.2 for a brief discussion relating tides to oil spill trajectories. See Sections 5.2.2 and 6.1 for more complete tidal information.

2.5 Storm Surges

Storm surges are a common oceanographic phenomena along the Bering Sea coast. The surges are caused by strong atmospheric winds blowing over a relatively shallow sea. Generally, the winds must be sustained from a limited set of directions and have a speed of over 25 kts. A surge is considered to be significant if it is over 1.7 m (6 ft). Maximum surges are thought to be near 3.75 m (12 ft) and at least one surge has been reported to 4.0 m (13.2 ft). A storm surge may be defined as an atmospherically generated and driven long ocean wave. Its slope is too small to be seen or measured but its depth can be estimated or measured by the extent of flooding of coastal areas. A surge can also be detected and measured by tide gauges, however, there are no permanent tide gauges north of the Aleutian

Islands. If significant tides (over 0.5 m) are present, the height of the surge is the height of the ocean's surface above projected tide levels. The primary significance of storm surges is that they provide a media for transporting oil from an oil spill, from the ocean area to inland areas. Storm surges are discussed elsewhere in this atlas in Section 3.7 (Factors Affecting Oil Spill Transport), Section 4.3 in Chapter 4.0 (Factors Affecting Oil Spill Containment), Section 5.5, Chapter 5.0 (Oceanography), Section 6.7, Chapter 6.0 (Climatology and Meteorology), and Appendix B which describes a storm forecast procedure and other information.

2.6 Climate and Meteorology

The climate and meteorology of the Bering Sea is an important consideration in Coast Guard operations and is the prime driving force for oil spill movements. It is the prime driving force for wave prediction models, superstructure icing, surface currents, sea ice movement and growth, and storm surges, in addition to oil spill trajectory models.

The Bering Sea is a relatively cold sea that is subject to considerable storm activity. Storms frequently move into the Bering Sea from the western Pacific Ocean but can approach from the central Pacific and even the Gulf of Alaska. Some of the storms from the western Pacific begin as typhoons which weaken sufficiently to be classified as extra-tropical cyclones when they reach the Bering. Some of the storms moving across the Pacific become huge by the time they reach the Bering Sea. These storms move slowly, and frequently have steep pressure gradients; consequently, the Bering Sea is subjected to strong wind forces. Figures 2.6-1 through 2.6-5 depict common pressure patterns in the Bering Sea. Figures 2.6-6 through 2.6-18 contain histographs (bar graphs) depicting climatological wind data for selected land stations. Maximum storm activity occurs during the fall and winter months.

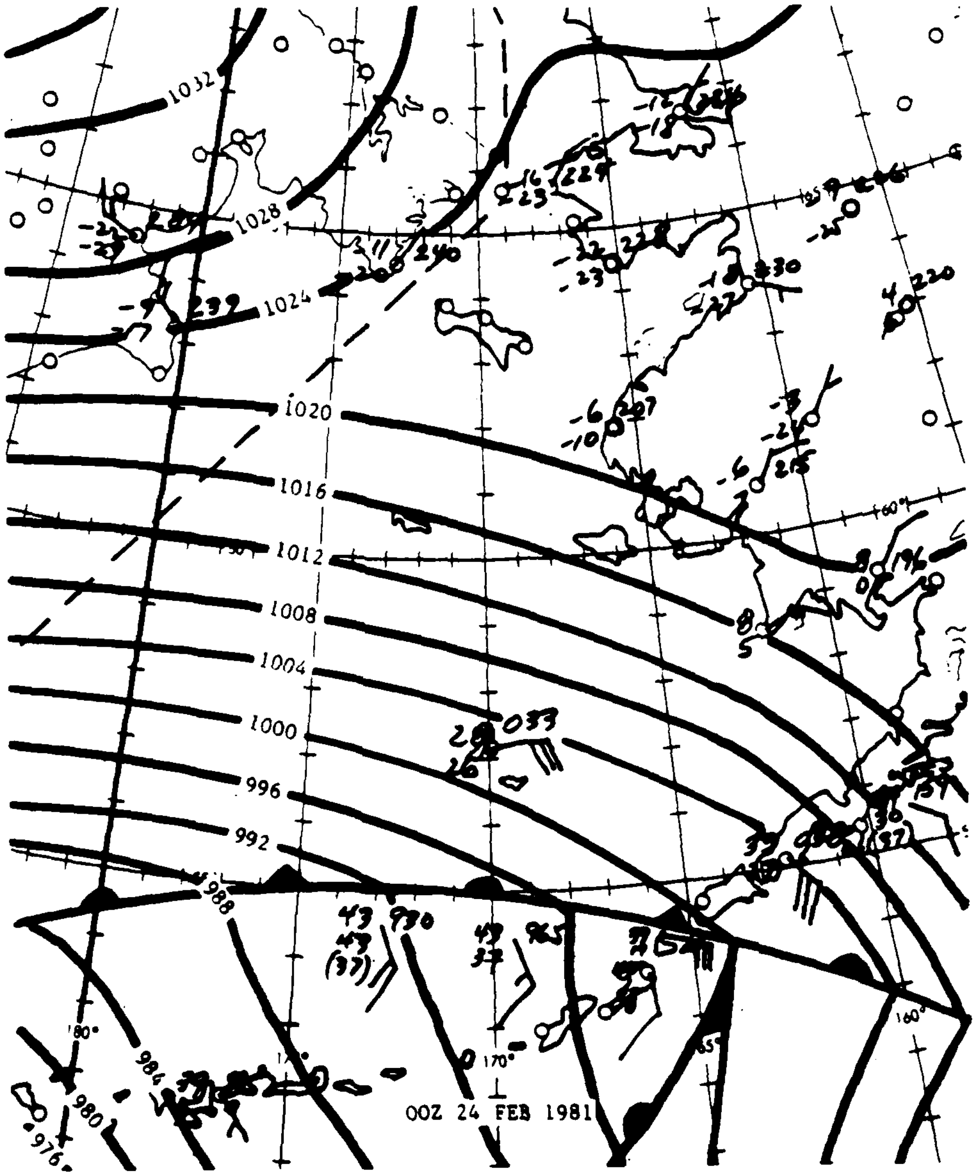


Figure 2.6-1. Surface pressure analysis depicting strong pressure gradient over the Bering Sea. The low pressure center is in the northern portion of the Pacific Ocean. (Lindsay and Comiskey, 1981)

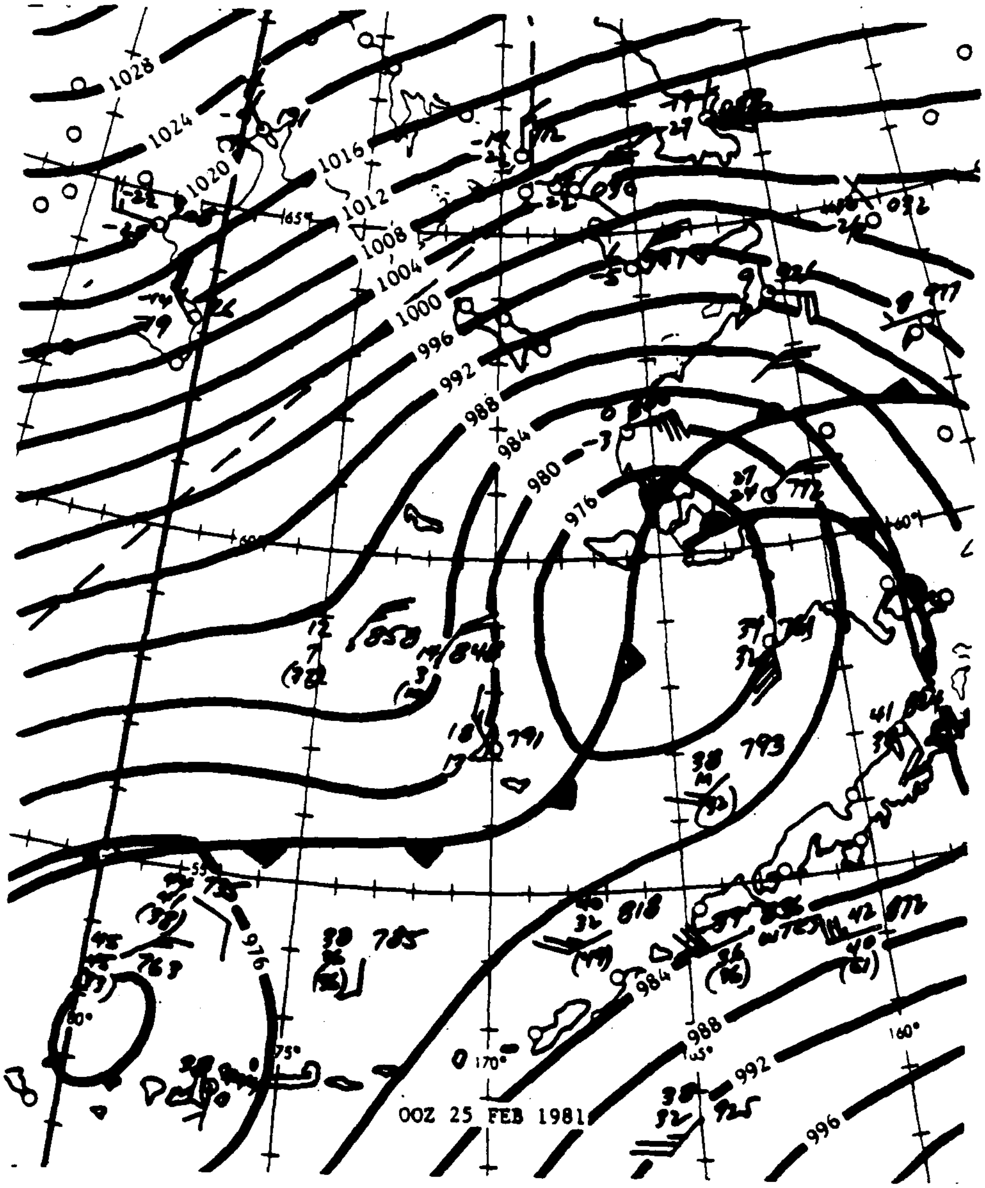


Figure 2.6-2. Surface pressure analysis depicting rapid formation of secondary low pressure center near Nunivak Island. Secondary low has formed on frontal system depicted in Figure 2.6-1. The primary center, on the international dateline, continues to move slowly. (Lindsay and Comiskey, 1981)

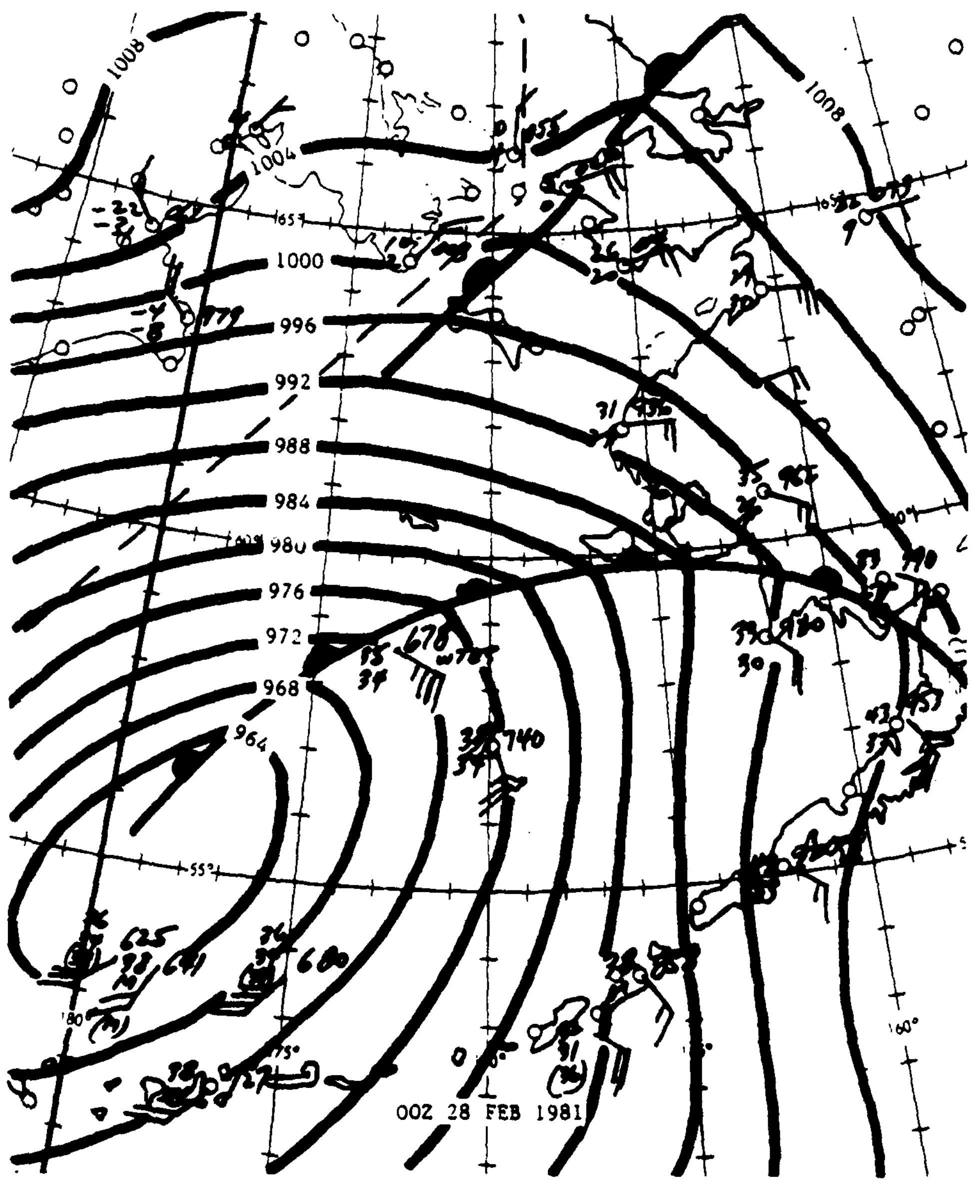


Figure 2.6-3. Surface pressure analysis depicting typical uncomplicated low pressure system centered in the southern Bering Sea. (Lindsay and Comiskey, 1981)

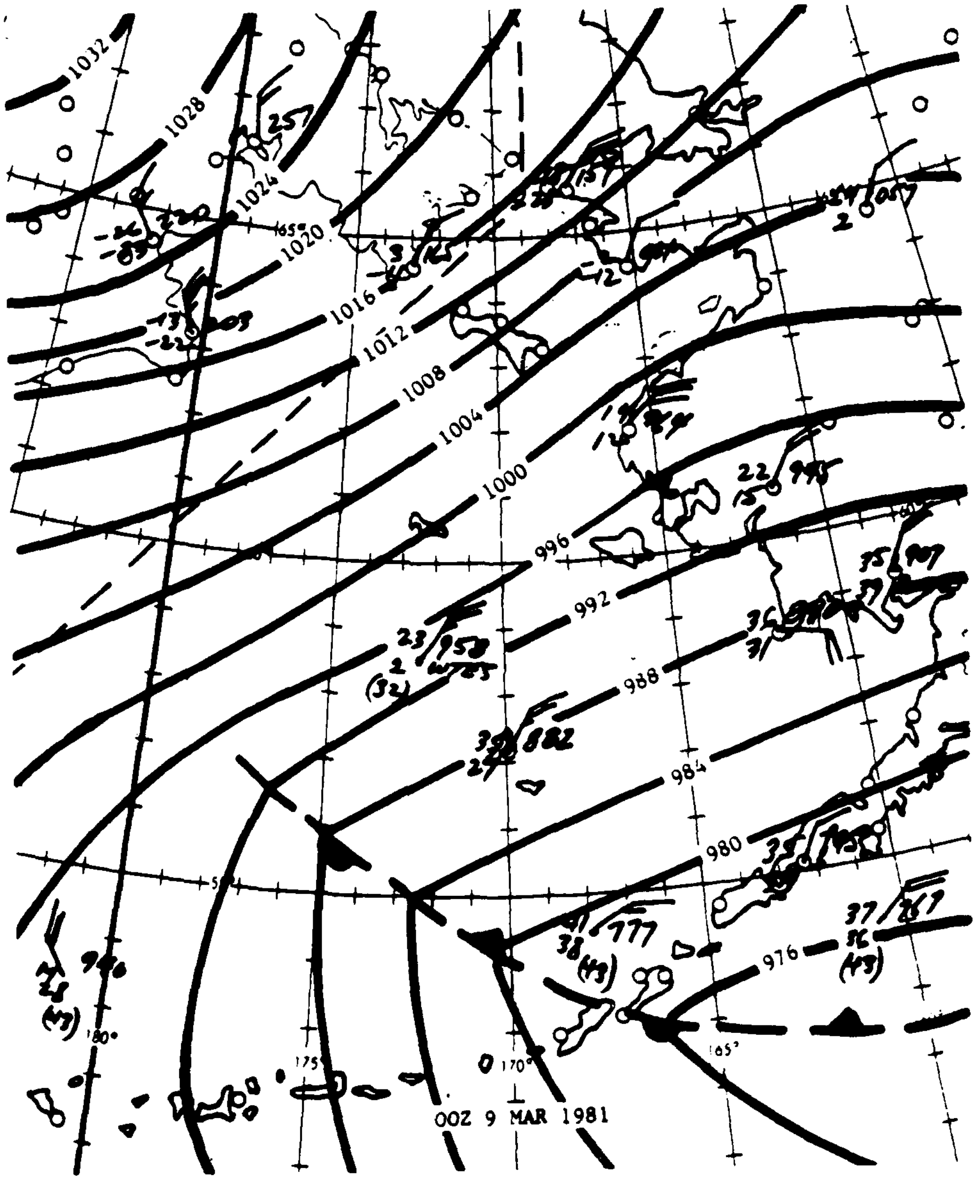


Figure 2.6-4. Surface pressure analysis depicting strong pressure gradient over the Bering Sea from storm centered south of the Alaska Peninsula (Lindsay and Comiskey, 1981)

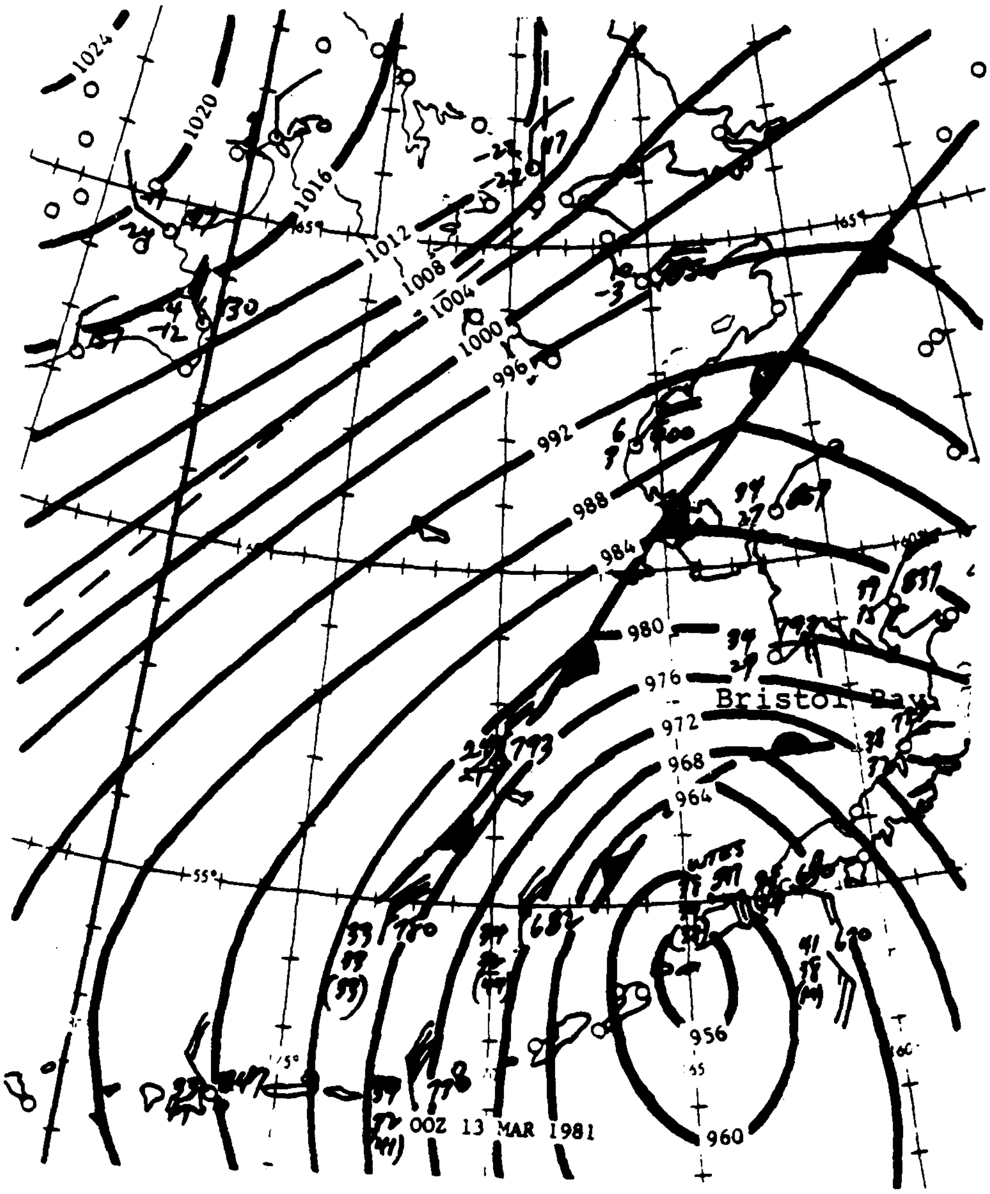


Figure 2.6-5. Surface pressure analysis depicting strong pressure gradient in the Bering Sea from storm moving into Bristol Bay. (Lindsay and Comiskey, 1981)

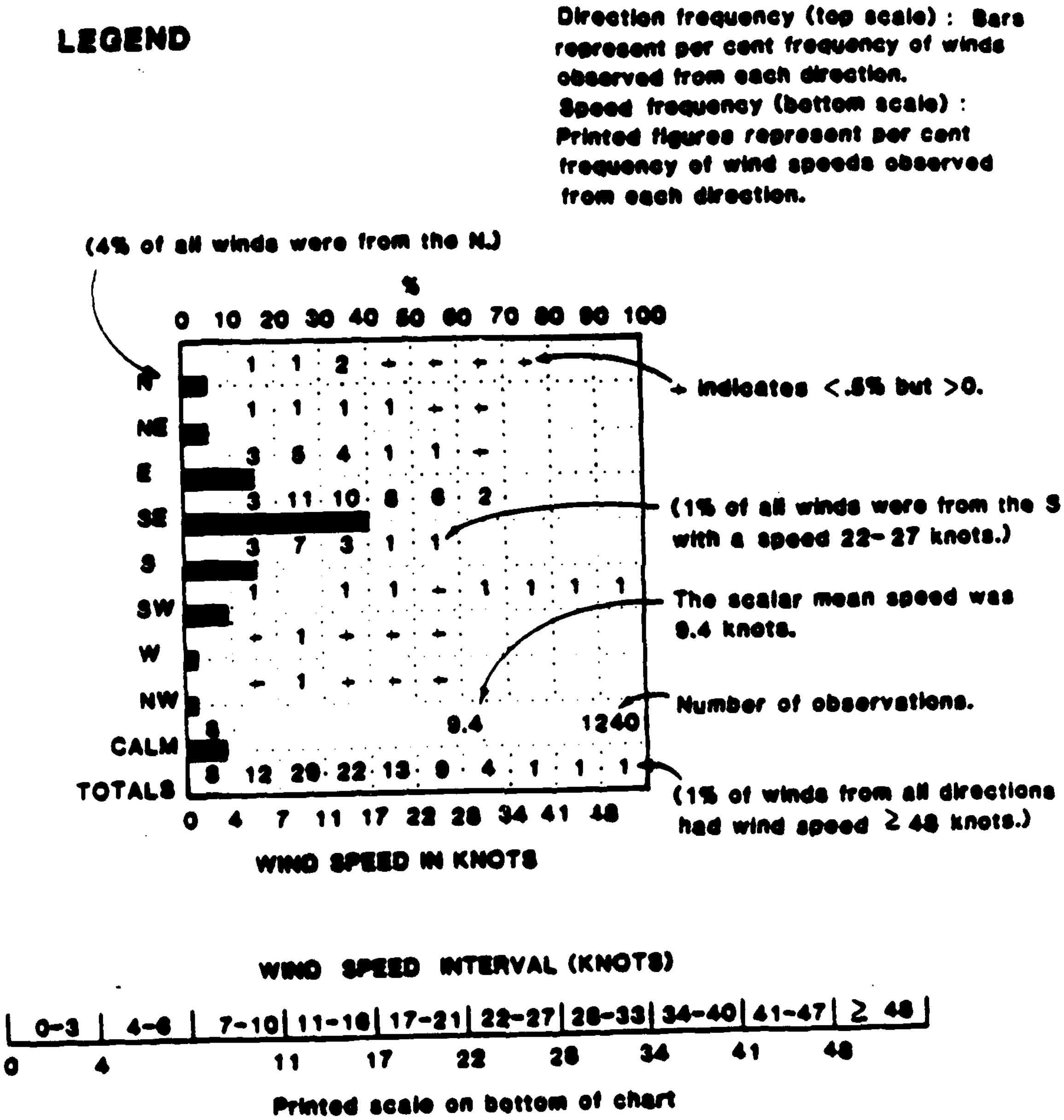


Figure 2.6-6. The above legend is provided to decipher the wind speed and direction histograms in Figures 2.6-7 through 2.6-18. (Adapted from Brower, et al., 1977).

JANUARY

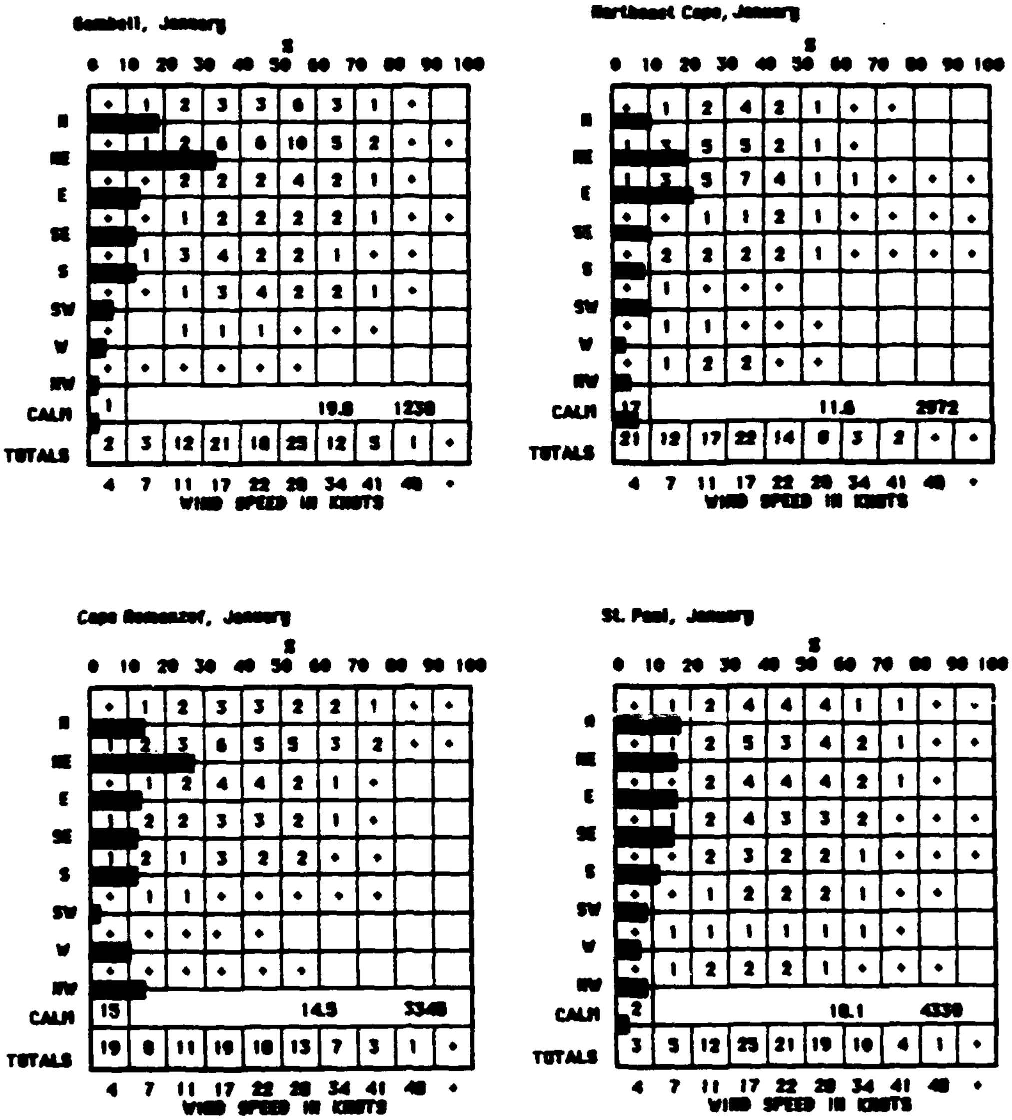


Figure 2.6-7. Wind speed and direction histograms for selected stations in the Bering Sea.

FEBRUARY

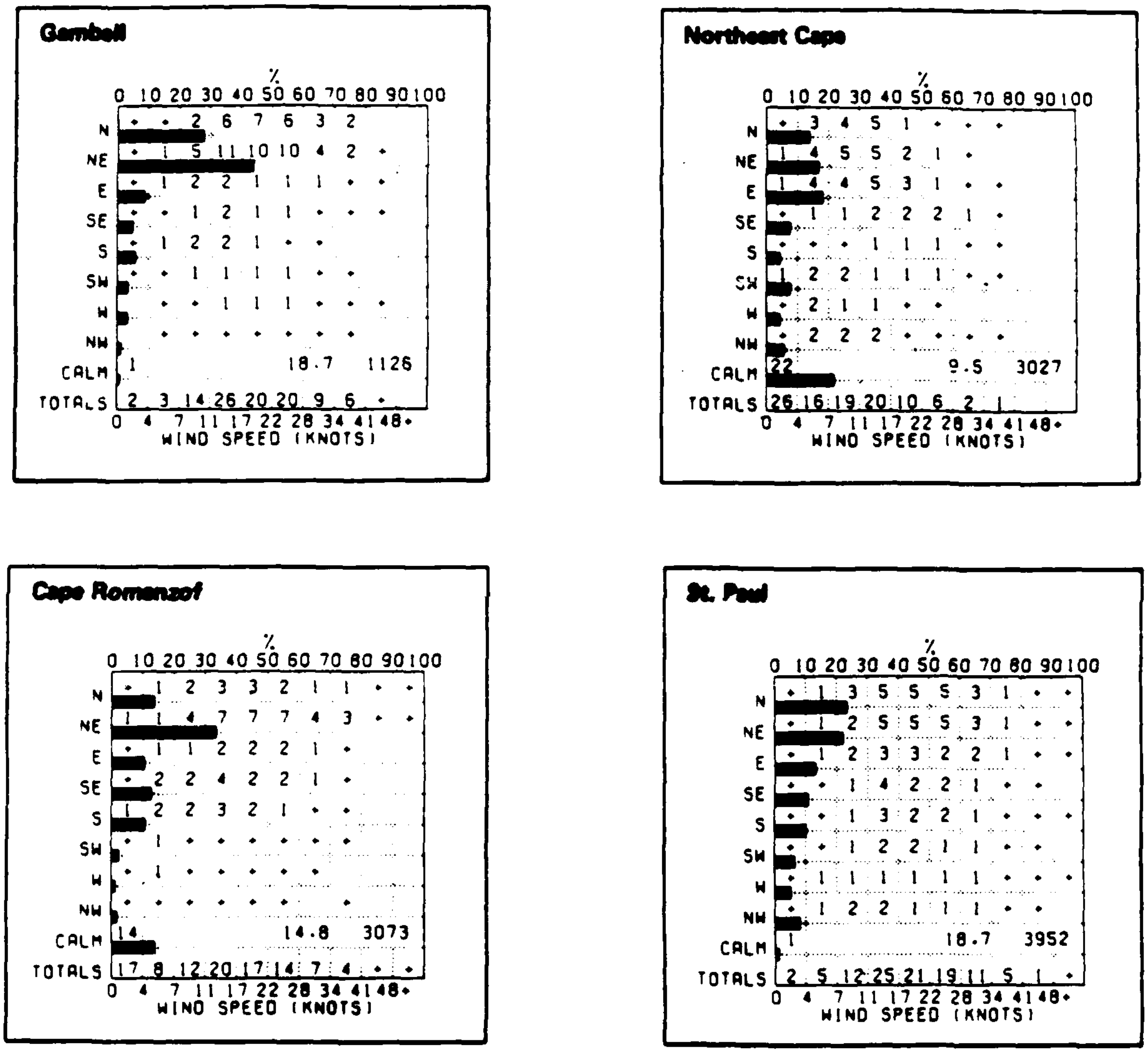


Figure 2.6-8. Wind speed and direction histograms for selected stations in the Bering Sea.

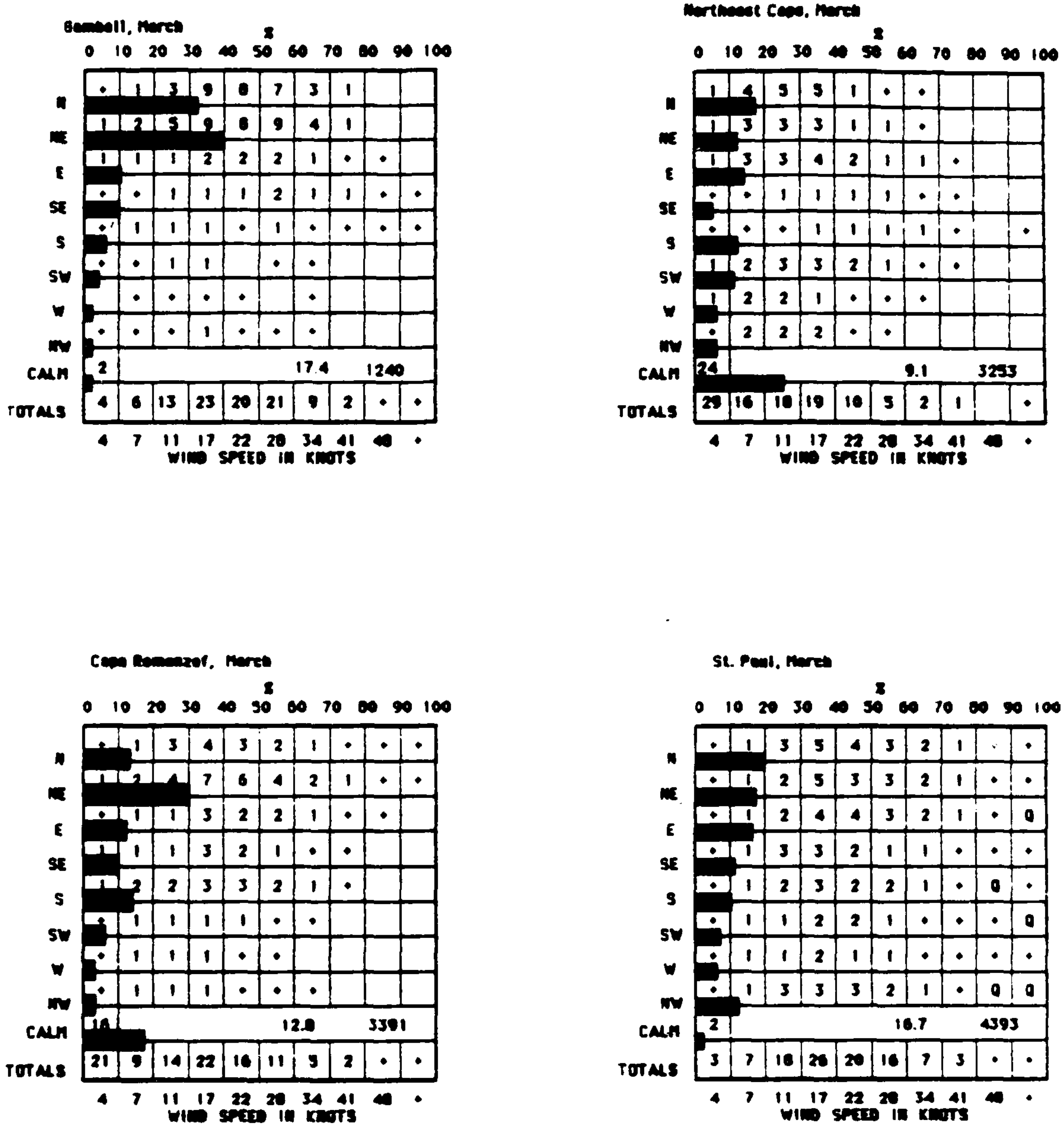


Figure 2.6-9. Wind speed and direction histograms for selected stations in the Bering Sea.

APRIL

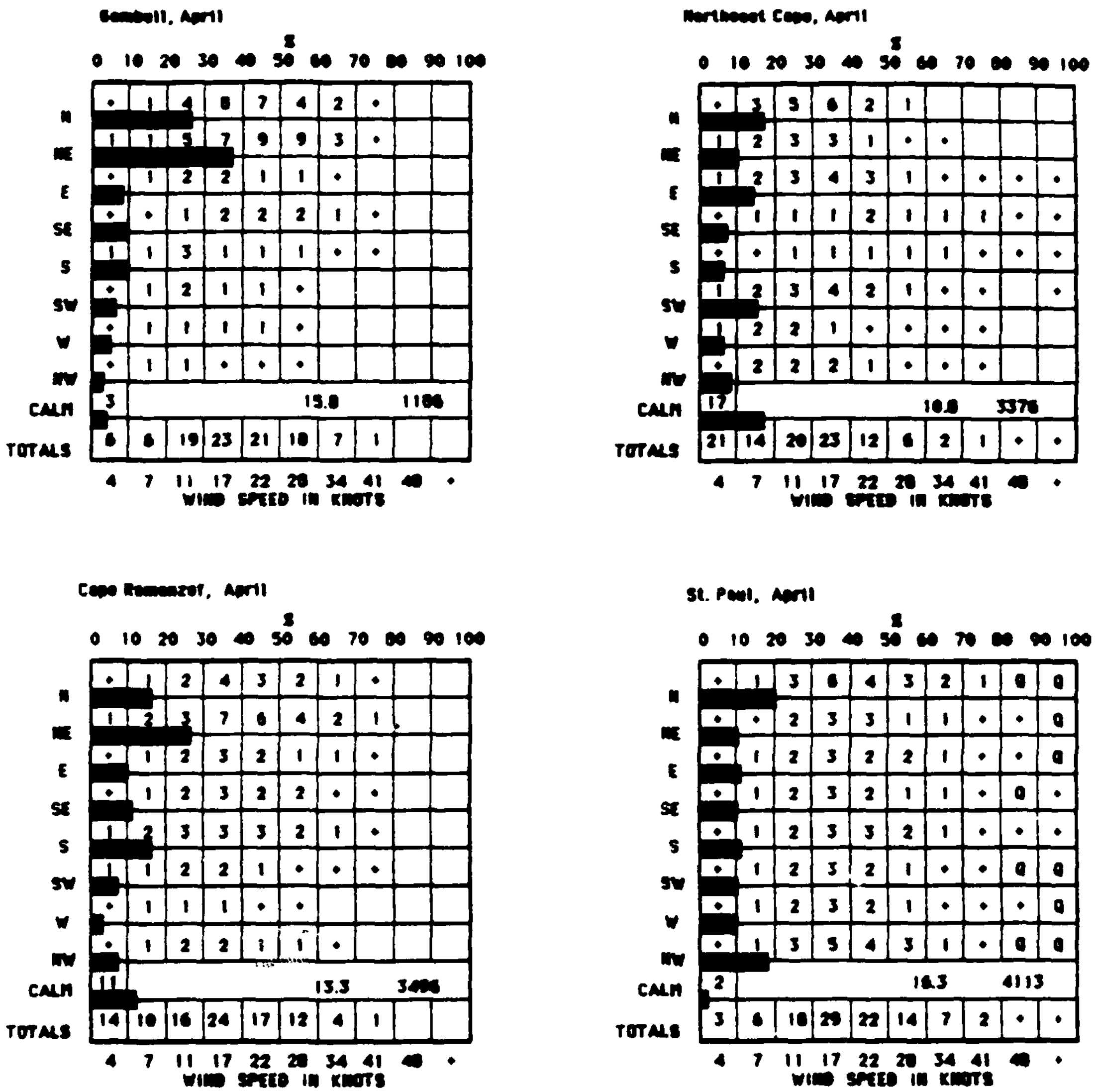


Figure 2.6-10. Wind speed and direction histograms for selected stations in the Bering Sea.

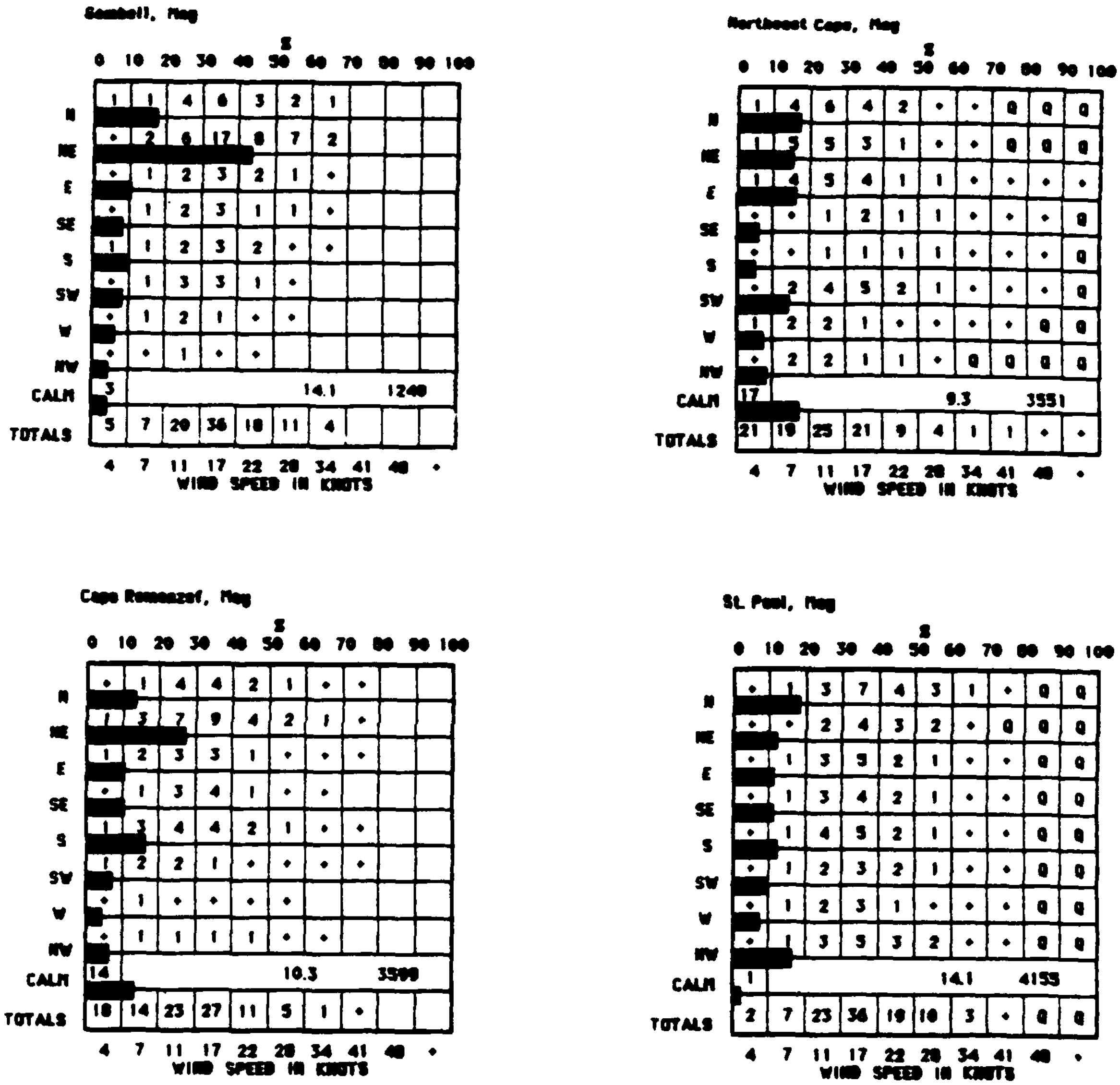


Figure 2.6-11. Wind speed and direction histograms for selected stations in the Bering Sea.

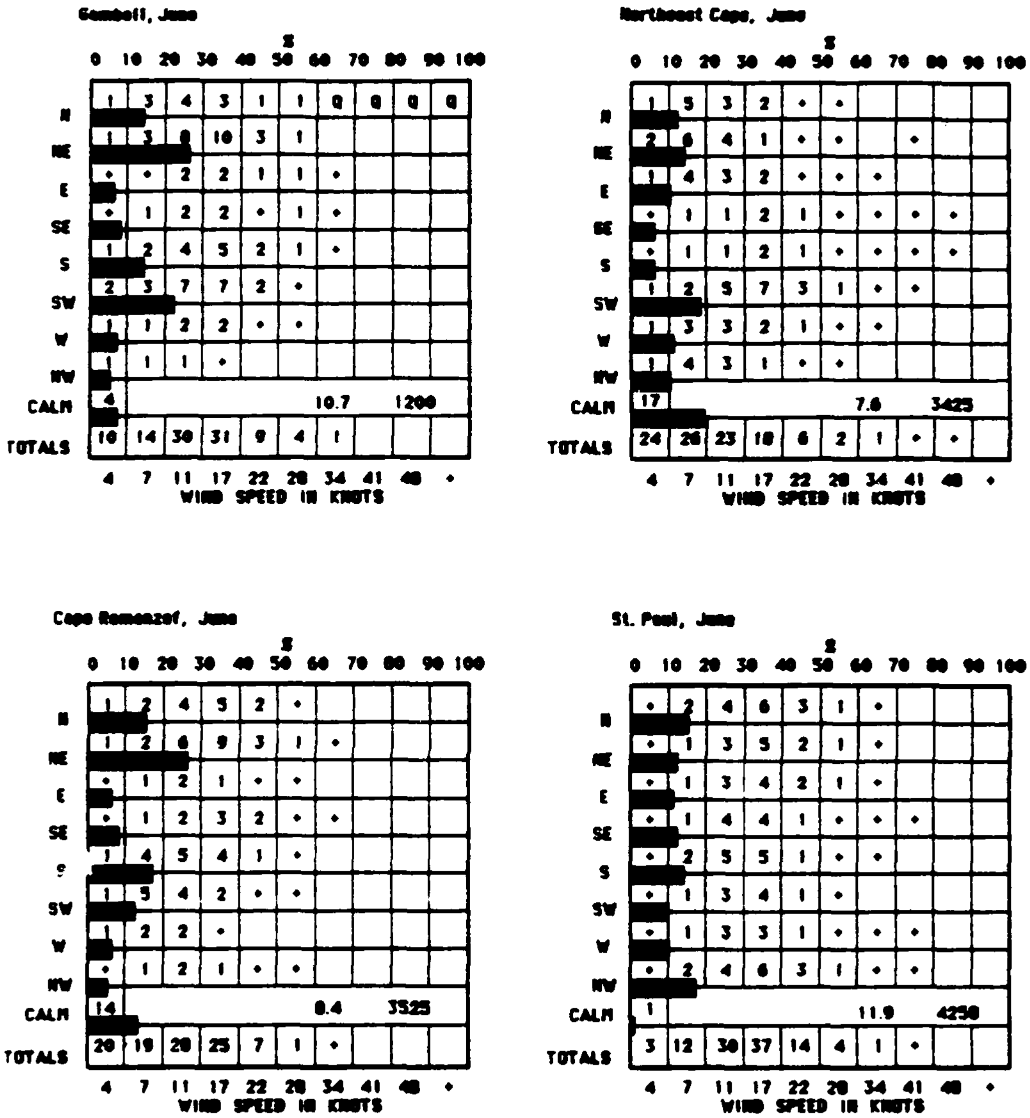


Figure 2.6-12. Wind speed and direction histograms for selected stations in the Bering Sea.

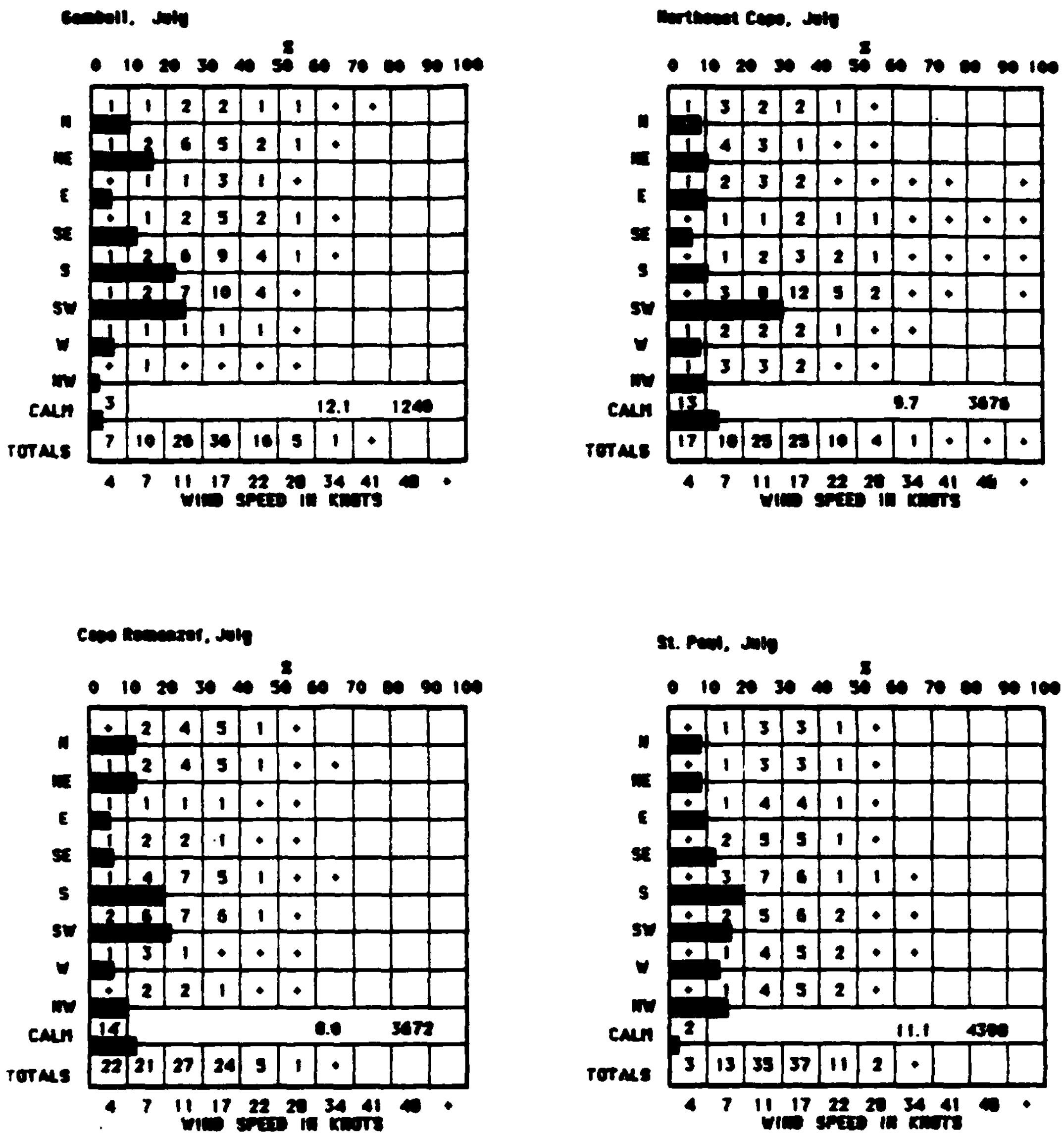


Figure 2.6-13. Wind speed and direction histograms for selected stations in the Bering Sea.

AUGUST

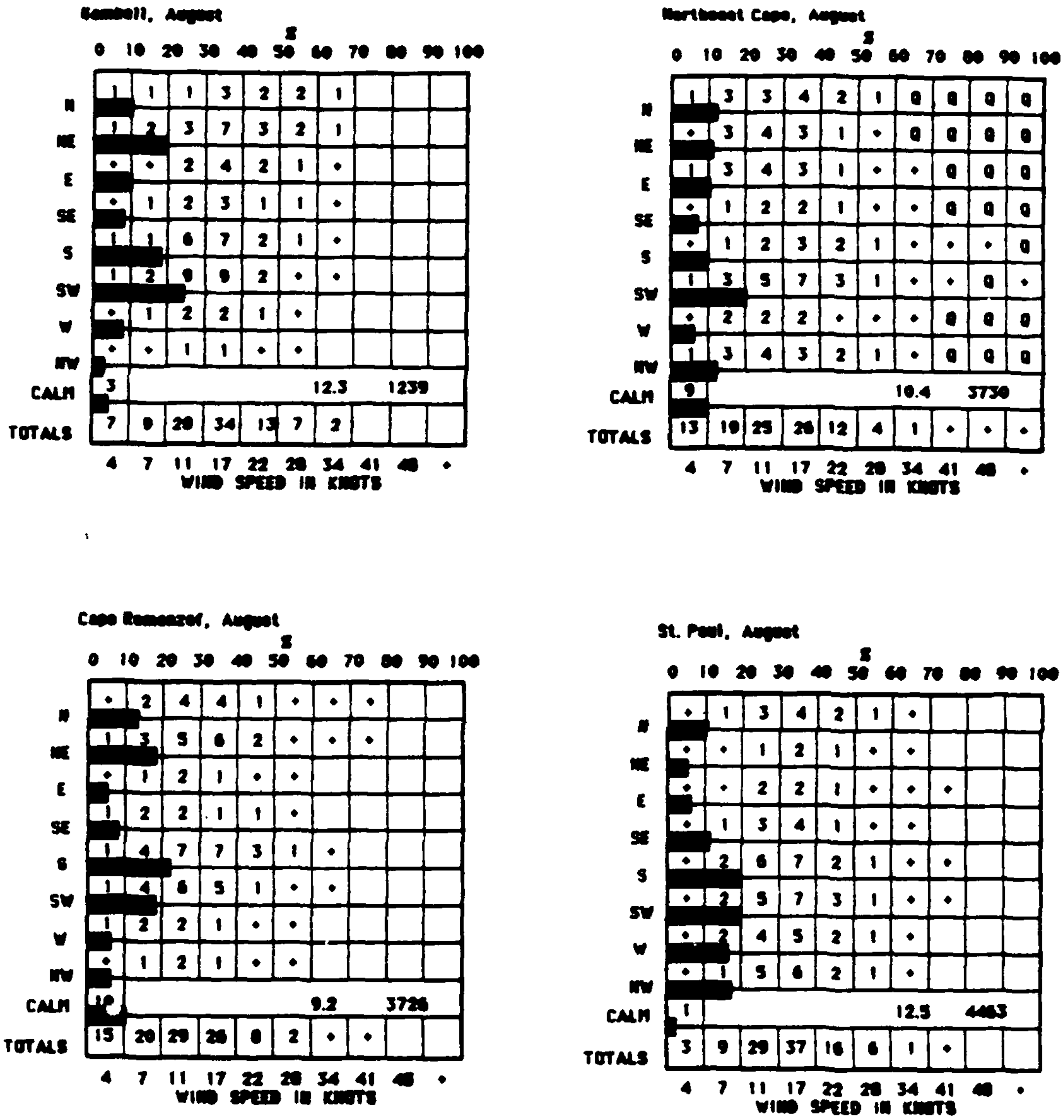


Figure 2.6-14. Wind speed and direction histograms for selected stations in the Bering Sea.

SEPTEMBER

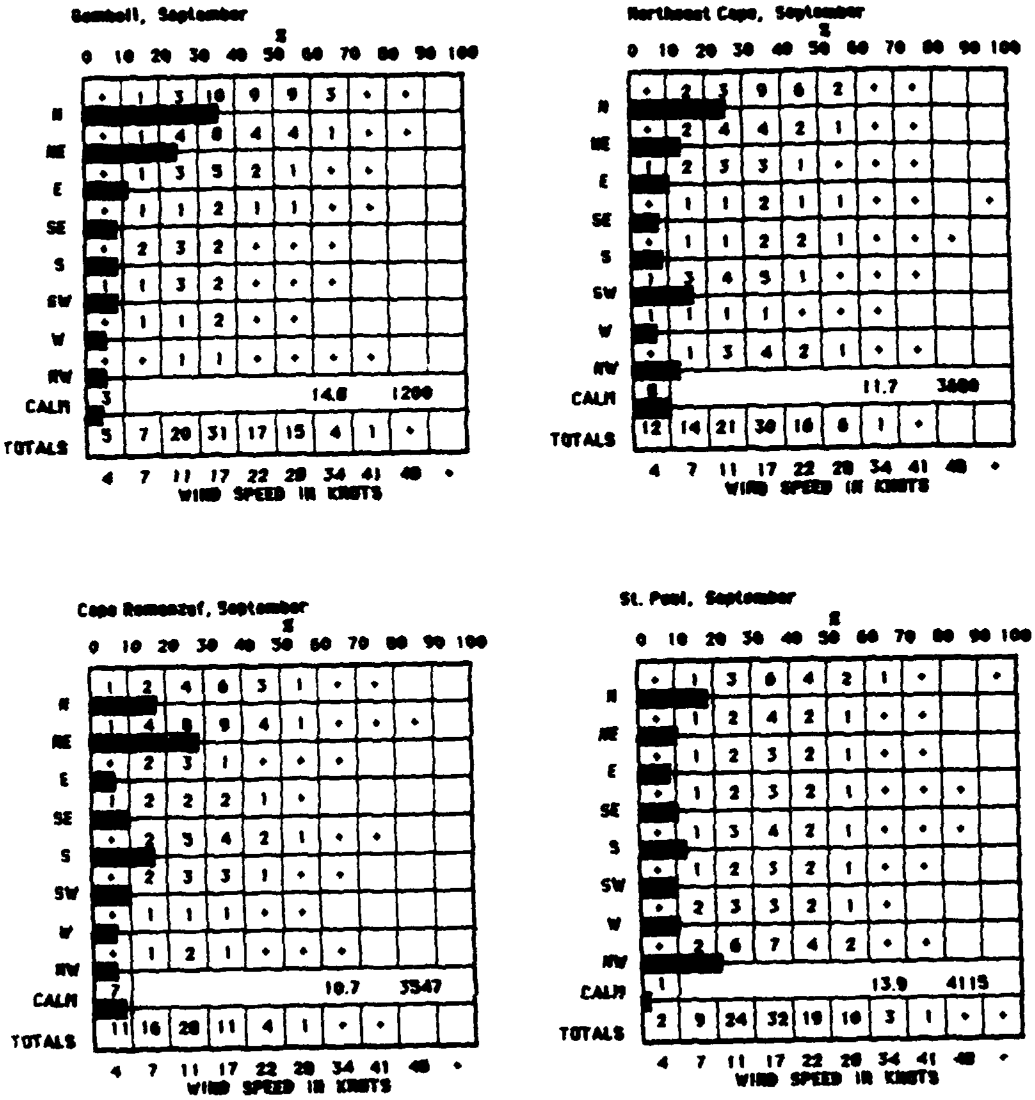


Figure 2.6-15. Wind speed and direction histograms for selected stations in the Bering Sea.

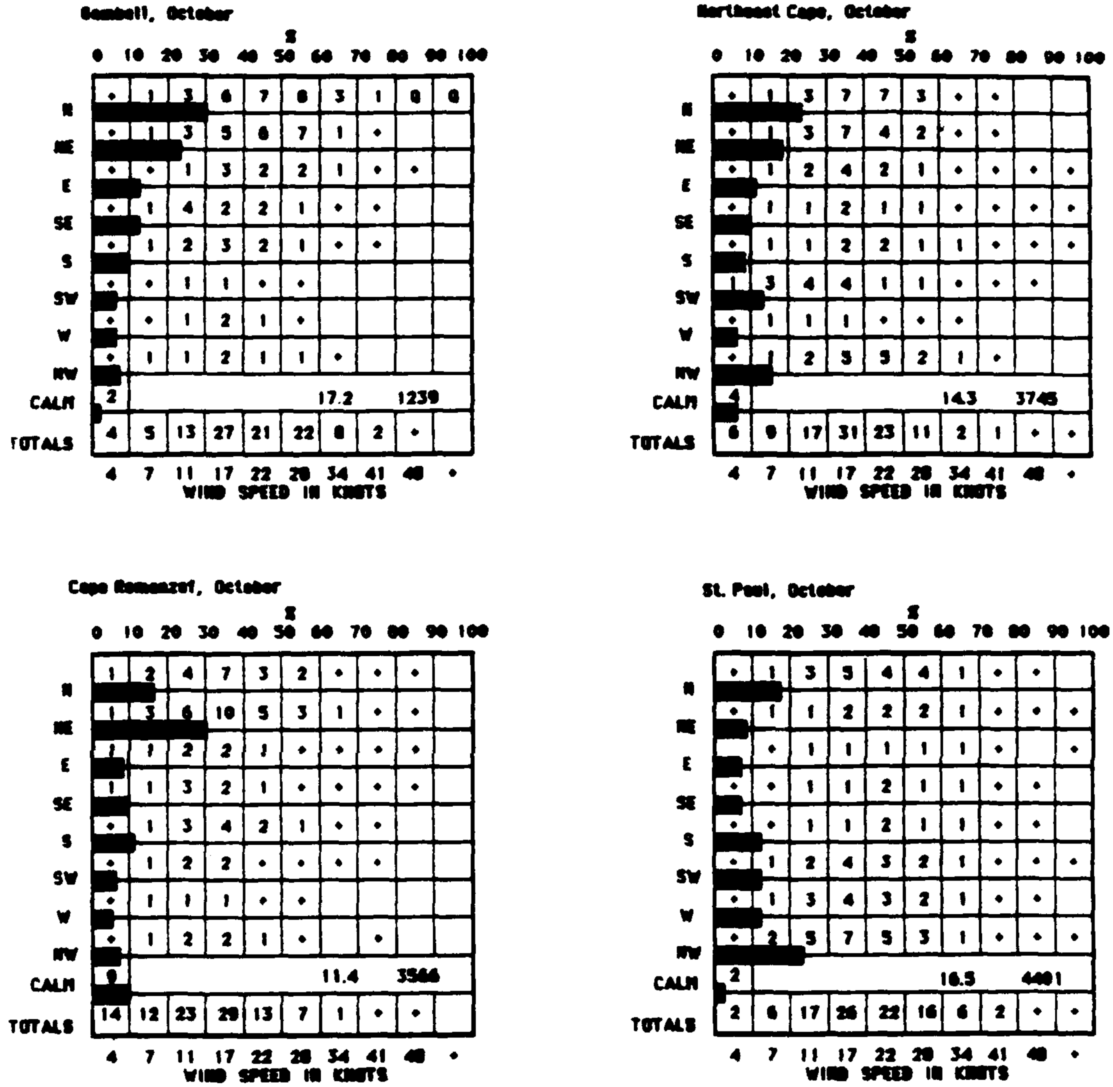


Figure 2.6-16. Wind speed and direction histograms for selected stations in the Bering Sea.

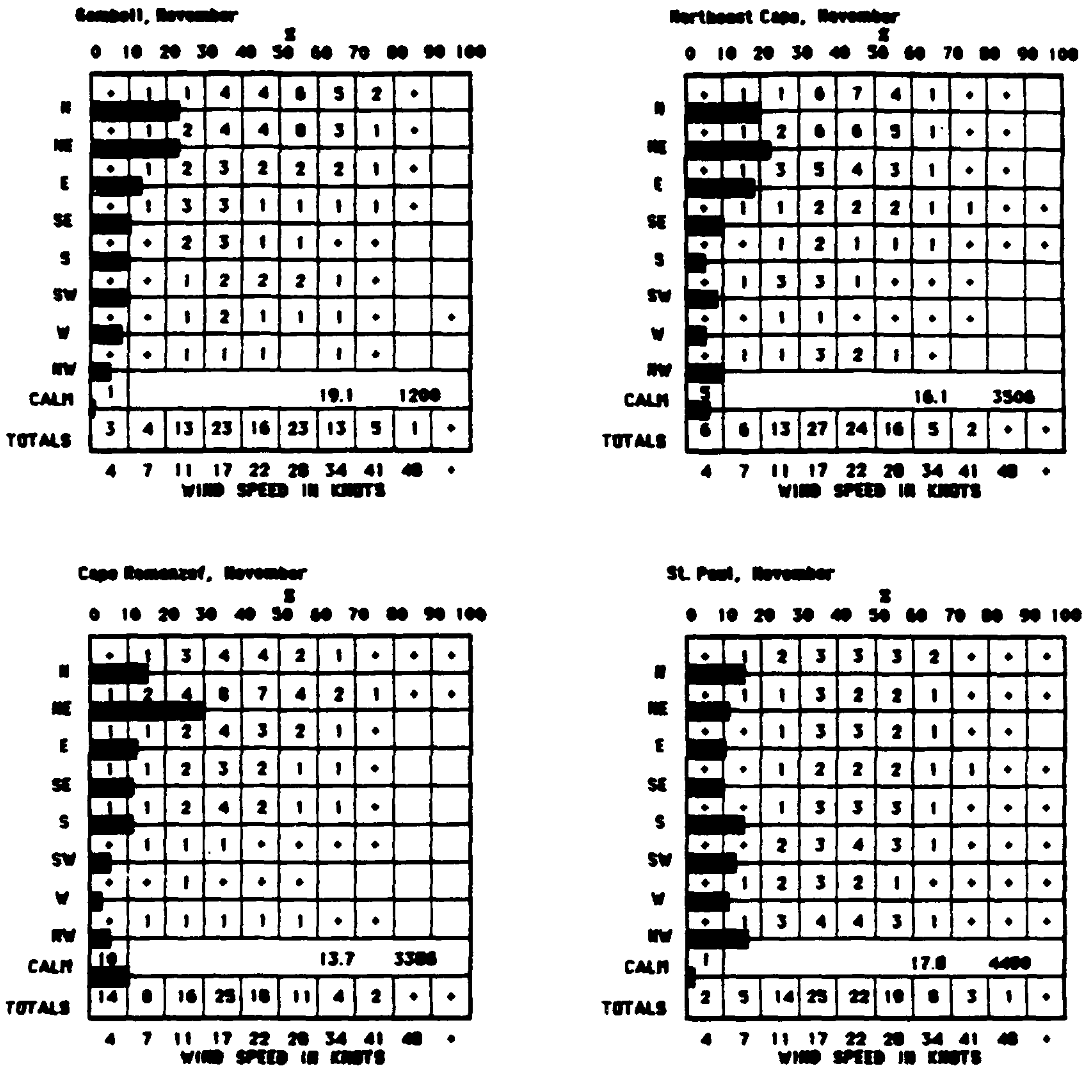


Figure 2.6-17. Wind speed and direction histograms for selected stations in the Bering Sea.

DECEMBER

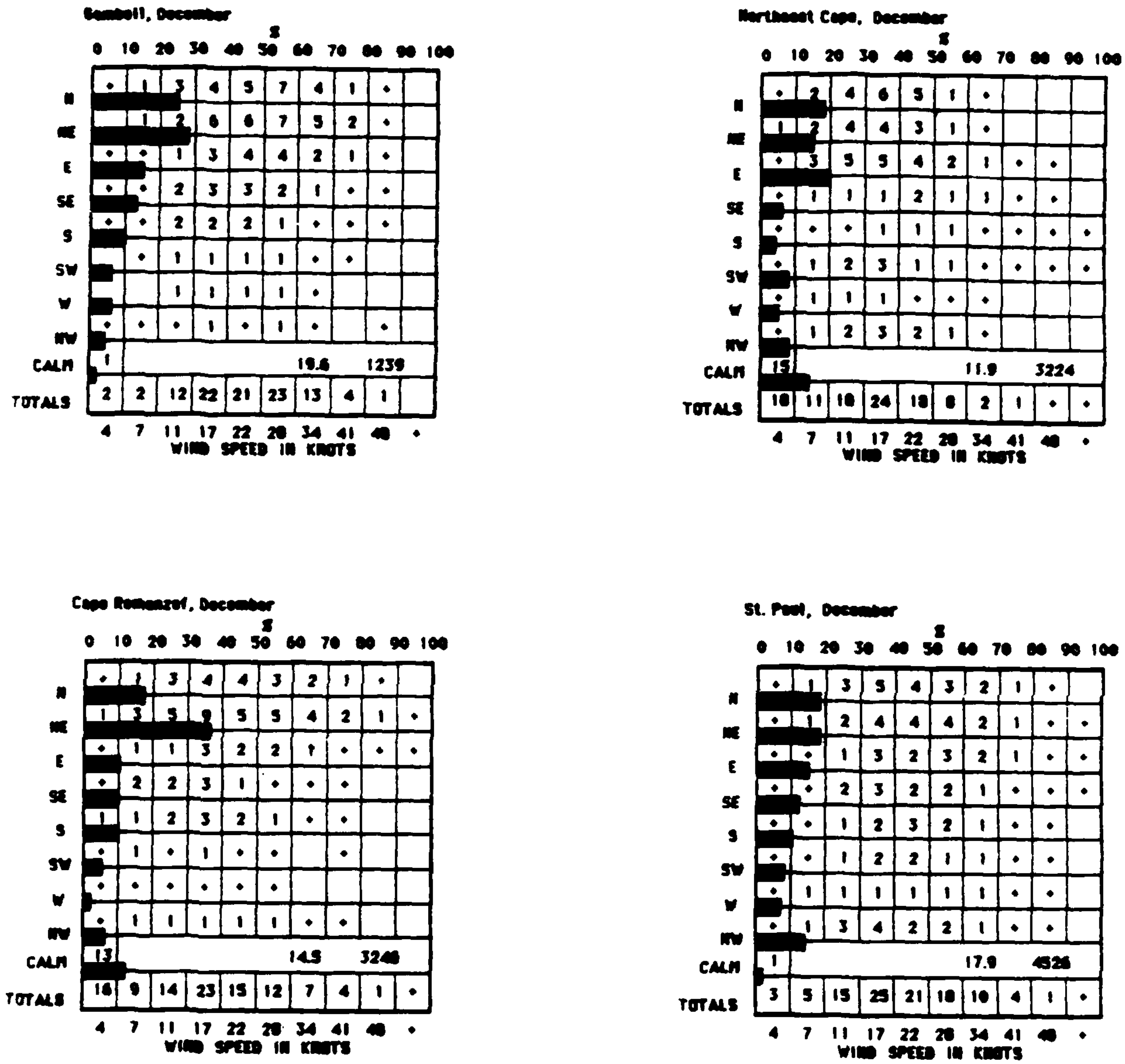


Figure 2.6-18. Wind speed and direction histograms for selected stations in the Bering Sea.

Gambell

VISIBILITY (columns); LOW CLOUD CEILING (rows)

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	1	4	16	29
50<80	0	0	•	0	•	1
35<50	•	0	0	•	•	•
20<35	0	•	•	1	2	1
10<20	1	1	2	3	8	3
6<10	•	1	3	3	3	1
3<6	•	1	1	1	1	0
1.5<3	•	•	0	0	0	0
0<1.5	7	2	•	0	0	0

1233

Northeast Cape

VISIBILITY (columns); LOW CLOUD CEILING (rows)

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	1	3	19	35
50<80	0	0	0	0	•	•
35<50	0	0	0	•	•	•
20<35	•	•	•	1	4	1
10<20	•	1	3	5	6	1
6<10	0	1	1	2	3	•
3<6	•	•	•	•	•	•
1.5<3	0	0	•	0	0	0
0<1.5	4	3	1	•	0	0

1838

JANUARY

Cape Romanzof

VISIBILITY (columns); LOW CLOUD CEILING (rows)

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	3	2	1	6	25	20
50<80	0	0	•	•	1	2
35<50	0	0	•	•	1	•
20<35	•	•	•	1	4	1
10<20	1	1	1	3	4	1
6<10	•	2	1	4	3	•
3<6	•	1	1	1	•	0
1.5<3	•	0	0	0	0	0
0<1.5	6	3	1	•	0	0

2223

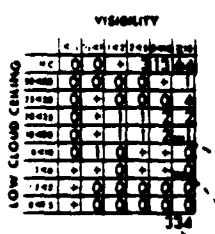
St. Paul

VISIBILITY (columns); LOW CLOUD CEILING (rows)

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	1	1	19	7
50<80	0	•	0	•	•	•
35<50	0	•	•	•	1	•
20<35	1	•	1	2	11	2
10<20	2	1	2	6	18	2
6<10	•	•	1	3	3	•
3<6	•	1	2	2	1	•
1.5<3	•	•	•	0	•	0
0<1.5	4	2	1	•	0	0

4058

Legend **Low cloud ceiling/visibility**



Percent frequency of simultaneous occurrence of specified low cloud ceilings (hundreds of feet) and visibilities (nautical miles).

Low cloud ceiling heights are estimated from the heights of low clouds (h) when low cloud amount (N_h) is ≥5/8.

Obscurations are included under ceiling 0 <1.5"

"N C" (no ceiling) includes bases of clouds ≥8000 feet as well as occurrences of N_h <5/8.

(2% of all observations reported ceiling ≥1000 but <2000 feet simultaneously with visibility ≥5 but <10 nautical miles.)

• indicates <.5% but >0.

Number of observations.

Figure 2.6-19. Histograms of low ceilings and visibility correlations for selected stations.

Gambell

LOW CLOUD CEILING / VISIBILITY

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	1	2	12	28
50<80	0	0	•	•	1	1
35<50	0	0	•	•	•	•
20<35	•	•	•	2	3	2
10<20	3	3	3	6	6	3
5<10	2	2	2	2	3	1
3<5	•	•	•	1	•	0
1.5<3	0	0	0	0	•	0
0<1.5	7	1	•	•	0	0

1121

Northeast Cape

LOW CLOUD CEILING / VISIBILITY

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	1	3	21	31
50<80	0	0	•	•	•	1
35<50	0	0	•	•	•	•
20<35	•	•	1	2	3	1
10<20	•	1	3	6	8	2
5<10	0	1	2	2	2	•
3<5	0	•	•	•	1	0
1.5<3	0	0	0	0	•	0
0<1.5	4	2	1	•	0	0

1984

FEBRUARY

Cape Romanzof

LOW CLOUD CEILING / VISIBILITY

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	2	3	2	5	27	16
50<80	•	•	•	•	1	1
35<50	0	•	0	•	1	•
20<35	•	•	•	1	5	1
10<20	1	1	1	3	5	1
5<10	1	2	2	2	2	•
3<5	•	•	•	•	•	0
1.5<3	0	0	•	0	0	0
0<1.5	4	3	•	•	0	0

2039

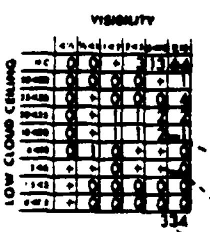
St. Paul

LOW CLOUD CEILING / VISIBILITY

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	1	•	1	1	22	8
50<80	•	0	•	•	•	•
35<50	0	0	•	0	1	•
20<35	1	•	•	1	7	2
10<20	3	2	3	6	17	2
5<10	1	1	1	2	4	•
3<5	1	1	1	1	1	•
1.5<3	•	•	•	•	•	0
0<1.5	5	1	•	•	0	0

3712

Legend **Low cloud ceiling/visibility**



Percent frequency of simultaneous occurrence of specified low cloud ceilings (hundreds of feet) and visibilities (nautical miles).

Low cloud ceiling heights are estimated from the height of low clouds (h) when low cloud amount (N_h) is ≥5/8.

Obscurations are included under ceiling "0 <1.5".

"N C" (no ceiling) includes bases of clouds ≥8000 feet as well as occurrences of N_h <5/8.

(2% of all observations reported ceiling ≥1000 but <2000 feet simultaneously with visibility ≥5 but <10 nautical miles.)

• indicates <.5% but >0.

Number of observations.

Figure 2.6-20. Histograms of low ceilings and visibility correlations for selected stations.

Gambell

LOW CLOUD CEILING \ VISIBILITY	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	1	3	12	33
50<80	0	•	0	•	•	1
35<50	0	•	•	•	1	•
20<35	•	1	•	1	2	1
10<20	1	2	3	6	7	2
6<10	1	2	3	3	4	•
3<6	•	•	•	1	1	•
1.5<3	0	0	0	0	0	0
0<1.5	5	2	•	•	0	0

1236

Northeast Cape

LOW CLOUD CEILING \ VISIBILITY	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	1	1	3	19	35
50<80	0	•	0	•	•	•
35<50	0	0	0	•	•	•
20<35	•	•	•	1	2	1
10<20	•	•	2	4	8	2
6<10	•	1	1	2	2	•
3<6	•	•	•	•	•	0
1.5<3	0	0	0	0	0	0
0<1.5	4	2	1	•	0	0

2092

MARCH

Cape Romanzof

LOW CLOUD CEILING \ VISIBILITY	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	2	3	1	5	25	20
50<80	•	•	•	•	2	1
35<50	0	•	•	•	1	•
20<35	1	1	•	1	4	1
10<20	1	1	1	3	3	•
6<10	1	2	2	3	3	•
3<6	•	1	1	1	1	0
1.5<3	0	0	0	0	0	0
0<1.5	7	3	•	•	0	0

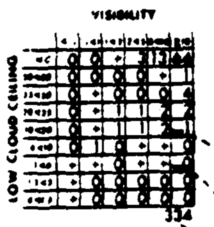
2272

St. Paul

LOW CLOUD CEILING \ VISIBILITY	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	1	•	1	2	18	12
50<80	0	0	0	•	•	•
35<50	•	•	0	•	1	1
20<35	•	•	•	1	6	3
10<20	2	2	2	5	14	3
6<10	1	2	1	2	4	•
3<6	1	2	2	2	1	•
1.5<3	•	•	•	•	•	0
0<1.5	5	1	•	•	0	0

4126

Legend **Low cloud ceiling/visibility**



Percent frequency of simultaneous occurrence of specified low cloud ceilings (hundreds of feet) and visibilities (nautical miles).

Low cloud ceiling heights are estimated from the height of low clouds (h) when low cloud amount (N_h) is ≥5/8.

Obscurations are included under ceiling "0 <1.5".

"N C" (no ceiling) includes bases of clouds ≥8000 feet as well as occurrences of N_h <5/8.

(2% of all observations reported ceiling ≥1000 but <2000 feet simultaneously with visibility ≥5 but <10 nautical miles.)

• indicates <.1% but >0.

Number of observations.

Figure 2.6-21. Histograms of low ceilings and visibility correlations for selected stations.

Gambell

VISIBILITY

LOW CLOUD CEILING	<½	½<1	1<2	2<5	5<10	≥10
NC	•	•	1	1	7	29
50<80	•	0	•	•	1	1
35<50	0	0	0	•	1	1
20<35	•	•	1	1	4	2
10<20	•	2	3	5	9	5
6<10	1	2	4	5	3	1
3<6	•	1	1	1	1	•
1.5<3	•	0	0	•	0	0
0<1.5	3	2	•	0	0	0

1180

Northeast Cape

VISIBILITY

LOW CLOUD CEILING	<½	½<1	1<2	2<5	5<10	≥10
NC	•	1	1	2	12	33
50<80	0	0	0	0	0	•
35<50	0	•	0	•	•	•
20<35	•	•	•	1	3	1
10<20	•	1	3	5	10	5
6<10	1	1	2	2	4	1
3<6	•	•	1	1	1	•
1.5<3	0	0	•	0	•	0
0<1.5	3	2	2	•	•	0

2199

APRIL

Cape Romanzof

VISIBILITY

LOW CLOUD CEILING	<½	½<1	1<2	2<5	5<10	≥10
NC	2	2	1	4	21	18
50<80	•	•	•	•	1	1
35<50	•	0	0	•	1	•
20<35	•	•	•	1	4	1
10<20	•	1	1	4	6	1
6<10	•	2	2	4	5	1
3<6	•	1	1	2	1	0
1.5<3	•	0	•	0	•	0
0<1.5	7	2	•	0	0	0

2387

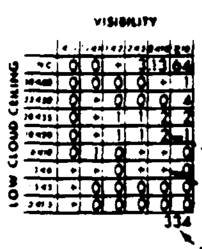
St. Paul

VISIBILITY

LOW CLOUD CEILING	<½	½<1	1<2	2<5	5<10	≥10
NC	•	•	•	1	15	10
50<80	0	0	0	•	1	•
35<50	0	0	0	•	1	1
20<35	•	•	•	1	7	4
10<20	2	1	2	5	17	5
6<10	•	1	1	3	4	1
3<6	•	2	2	3	2	•
1.5<3	•	•	•	•	•	•
0<1.5	5	1	•	•	•	0

3995

Legend **Low cloud ceiling/visibility**



Percent frequency of simultaneous occurrence of specified low cloud ceilings (hundreds of feet) and visibilities (nautical miles)

Low cloud ceiling heights are estimated from the height of low clouds (h) when low cloud amount (N_h) is ≥5/8

Obscurations are included under ceiling 0 <1.5

"N C" (no ceiling) includes bases of clouds ≥8000 feet as well as occurrences of N_h <5/8.

(2% of all observations reported ceiling ≥1000 but <2000 feet simultaneously with visibility ≥5 but <10 nautical miles.)

• indicates < 5% but >0.

Number of observations.

Figure 2.6-22. Histograms of low ceilings and visibility correlations for selected stations.

Gambell

LOW CLOUD CEILING / VISIBILITY

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	0	•	•	4	13
50<80	0	0	0	•	•	1
35<50	•	0	0	•	•	•
20<35	•	0	•	•	1	3
10<20	0	•	1	2	8	8
6<10	•	1	3	4	14	9
3<6	•	1	2	4	4	1
1.5<3	•	•	1	•	•	0
0<1.5	4	3	1	•	0	0

1236

Northeast Cape

LOW CLOUD CEILING / VISIBILITY

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	1	4	22
50<80	0	0	0	•	•	1
35<50	0	0	•	•	•	1
20<35	•	•	•	•	2	4
10<20	•	•	1	3	9	12
6<10	0	1	2	3	8	6
3<6	•	1	2	3	3	1
1.5<3	0	0	•	•	•	0
0<1.5	3	2	1	1	0	0

2391

MAY

Cape Romanzof

LOW CLOUD CEILING / VISIBILITY

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	1	16	21
50<80	0	•	•	•	2	1
35<50	0	0	0	•	1	1
20<35	•	•	•	1	6	4
10<20	•	•	1	2	8	3
6<10	•	1	2	4	5	2
3<6	•	2	2	3	3	•
1.5<3	•	•	•	•	•	•
0<1.5	4	2	1	•	0	0

2502

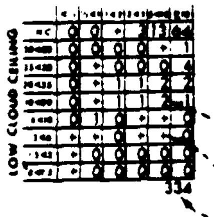
St. Paul

LOW CLOUD CEILING / VISIBILITY

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	1	11	8
50<80	•	0	0	0	•	•
35<50	•	0	0	•	1	1
20<35	•	•	•	•	7	4
10<20	•	•	1	3	15	5
6<10	•	•	1	3	5	1
3<6	1	2	4	6	6	1
1.5<3	•	1	1	1	•	•
0<1.5	7	3	1	•	•	0

4131

Legend **Low cloud ceiling/visibility**



Percent frequency of simultaneous occurrence of specified low cloud ceilings (hundreds of feet) and visibilities (nautical miles).

Low cloud ceiling heights are estimated from the height of low clouds (h) when low cloud amount (N_h) is ≥5/8.

Obscurations are included under ceiling "0 <1.5".

"N C" (no ceiling) includes bases of clouds ≥8000 feet as well as occurrences of N_h <5/8.

(2% of all observations reported ceiling ≥1000 but <2000 feet simultaneously with visibility ≥5 but <10 nautical miles.)

• indicates < 5% but >0.

Number of observations.

Figure 2.6-23. Histograms of low ceilings and visibility correlations for selected stations.

Gambell

VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	1	•	•	•	4	22
50<80	0	0	•	0	•	2
35<50	0	0	0	•	0	1
20<35	•	0	0	•	1	2
10<20	0	•	•	1	3	4
6<10	•	•	1	4	9	5
3<6	•	1	4	5	7	2
1.5<3	:	1	1	•	•	•
0<1.5	12	4	1	•	0	0

1198

Northeast Cape

VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	:	:	•	1	5	26
50<80	0	•	•	•	•	2
35<50	0	•	0	•	•	2
20<35	•	•	0	•	:	4
10<20	0	•	•	3	8	12
6<10	0	•	2	3	8	4
3<6	•	1	2	3	4	1
1.5<3	•	•	•	•	•	0
0<1.5	5	1	1	•	0	0

2336

JUNE

Cape Romanzof

VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	1	•	2	13	17
50<80	0	0	0	•	1	1
35<50	0	0	0	0	1	1
20<35	0	•	•	•	3	4
10<20	0	•	•	2	8	4
6<10	0	•	1	4	10	4
3<6	0	1	1	3	5	1
1.5<3	0	•	•	•	•	0
0<1.5	5	3	1	1	•	0

2458

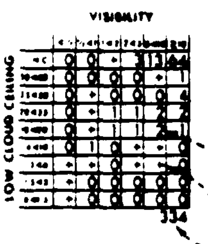
St. Paul

VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	1	•	•	1	9	7
50<80	0	0	0	0	1	•
35<50	•	0	0	•	1	1
20<35	•	•	0	•	4	3
10<20	•	•	•	1	13	5
6<10	•	•	1	3	7	1
3<6	1	2	4	8	8	1
1.5<3	•	1	1	1	•	•
0<1.5	9	3	1	•	•	0

4232

Legend **Low cloud ceiling/visibility**



Percent frequency of simultaneous occurrence of specified low cloud ceilings (hundreds of feet) and visibilities (nautical miles).

Low cloud ceiling heights are estimated from the height of low clouds (h) when low cloud amount (N_h) is ≥5/8.

Obscurations are included under ceiling 0 <1.5

"N C" (no ceiling) includes bases of clouds ≥8000 feet as well as occurrences of N_h <5/8.

(2% of all observations reported ceiling ≥1000 but <2000 feet simultaneously with visibility ≥5 but <10 nautical miles.)

• indicates <.5% but >0.

Number of observations.

Figure 2.6-24. Histograms of low ceilings and visibility correlations for selected stations.

Gambell

VISIBILITY (columns); LOW CLOUD CEILING (rows)

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	1	4	15
50<80	0	0	•	0	•	2
35<50	0	0	0	0	•	•
20<35	0	0	0	•	1	3
10<20	0	0	0	•	3	5
6<10	•	•	1	3	13	6
3<6	•	2	3	7	11	1
1.5<3	•	1	1	1	•	0
0<1.5	8	5	1	•	•	0

1215

Northeast Cape

VISIBILITY (columns); LOW CLOUD CEILING (rows)

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	1	7	24
50<80	•	0	•	•	•	1
35<50	0	0	0	0	•	•
20<35	•	•	•	•	•	3
10<20	0	•	1	3	8	10
6<10	•	•	2	4	10	4
3<6	•	1	2	3	4	1
1.5<3	0	0	•	•	•	•
0<1.5	3	2	1	•	0	0

2513

JULY

Cape Romanzof

VISIBILITY (columns); LOW CLOUD CEILING (rows)

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	2	13	13
50<80	0	•	0	•	1	•
35<50	0	0	0	0	•	•
20<35	0	0	0	•	2	3
10<20	0	•	•	1	6	5
6<10	0	•	1	3	13	5
3<6	0	1	2	6	7	1
1.5<3	•	•	•	•	•	0
0<1.5	6	4	1	•	0	0

2563

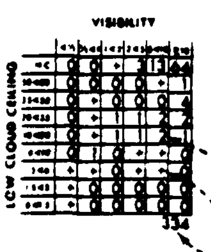
St. Paul

VISIBILITY (columns); LOW CLOUD CEILING (rows)

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	1	•	•	•	6	4
50<80	•	•	0	0	•	•
35<50	•	0	•	•	•	•
20<35	•	•	•	•	3	2
10<20	•	•	•	1	10	3
6<10	•	•	1	3	8	1
3<6	1	3	6	9	8	1
1.5<3	1	1	1	1	•	•
0<1.5	16	4	2	•	0	•

4376

Legend **Low cloud ceiling/visibility**



Percent frequency of simultaneous occurrence of specified low cloud ceilings (hundreds of feet) and visibilities (nautical miles).

Low cloud ceiling heights are estimated from the height of low clouds (h) when low cloud amount (N_h) is ≥5/8.

Obscurations are included under ceiling "0 <1.5".

"N C" (no ceiling) includes bases of clouds ≥8000 feet as well as occurrences of N_h <5/8.

(2% of all observations reported ceiling ≥1000 but <2000 feet simultaneously with visibility ≥5 but <10 nautical miles.)

• indicates <.5% but >0.

Number of observations.

Figure 2.6-25. Histograms of low ceilings and visibility correlations for selected stations.

Gambell

LOW CLOUD CEILING	VISIBILITY <1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	•	3	16
50<80	0	•	0	0	•	1
35<50	0	0	0	0	1	1
20<35	0	0	•	•	1	5
10<20	0	0	0	•	5	7
6<10	0	•	1	5	11	7
3<6	1	1	3	4	8	2
1.5<3	•	1	1	1	0	0
0<1.5	9	2	1	•	•	0
						1228

Northeast Cape

LOW CLOUD CEILING	VISIBILITY <1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	1	3	14
50<80	•	0	0	•	•	1
35<50	0	0	0	0	•	1
20<35	0	•	•	•	2	6
10<20	0	•	1	4	10	13
6<10	•	1	3	5	10	4
3<6	•	1	3	4	4	1
1.5<3	•	0	•	•	•	•
0<1.5	3	2	1	•	0	0
						2534

AUGUST

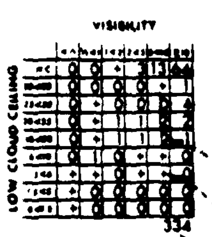
Cape Romanzof

LOW CLOUD CEILING	VISIBILITY <1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	1	6	10
50<80	0	0	0	0	1	1
35<50	0	0	0	0	1	•
20<35	0	0	•	•	3	3
10<20	0	•	•	2	12	8
6<10	0	•	1	5	13	4
3<6	•	1	2	7	5	1
1.5<3	0	•	•	•	0	•
0<1.5	3	5	2	1	0	•
						2576

St. Paul

LOW CLOUD CEILING	VISIBILITY <1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	1	7	4
50<80	•	0	0	•	•	•
35<50	0	0	0	•	•	•
20<35	•	•	0	•	4	2
10<20	•	•	•	1	10	5
6<10	•	•	1	3	9	1
3<6	1	3	6	10	7	1
1.5<3	•	2	1	1	•	•
0<1.5	12	3	1	•	0	•
						4437

Legend **Low cloud ceiling/visibility**



Percent frequency of simultaneous occurrence of specified low cloud ceilings (hundreds of feet) and visibilities (nautical miles).

Low cloud ceiling heights are estimated from the height of low clouds (h) when low cloud amount (N_h) is ≥5/8.

Obscurations are included under ceiling "0 <1.5"

"N C" (no ceiling) includes bases of clouds ≥8000 feet as well as occurrences of N_h <5/8.

(2% of all observations reported ceiling ≥1000 but <2000 feet simultaneously with visibility ≥5 but <10 nautical miles)

• indicates <.5% but >0.

Number of observations

Figure 2.6-26. Histograms of low ceilings and visibility correlations for selected stations.

Gambell

VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	0	0	•	3	20
50<80	•	0	0	0	1	2
35<50	0	0	0	0	1	2
20<35	0	0	0	1	5	12
10<20	0	•	•	1	11	16
6<10	0	•	1	4	6	3
3<6	0	1	1	2	2	1
1.5<3	•	•	•	•	•	0
0<1.5	2	1	•	•	•	0

1198

Northeast Cape

VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	1	3	15
50<80	0	•	0	•	•	1
35<50	•	•	•	•	•	1
20<35	0	0	•	•	4	9
10<20	0	•	1	3	12	15
6<10	•	•	1	7	9	2
3<6	•	1	2	3	3	•
1.5<3	0	0	•	•	•	•
0<1.5	2	1	1	•	•	0

2480

SEPTEMBER

Cape Romanzof

VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	1	7	14
50<80	0	•	0	0	1	2
35<50	0	0	0	0	1	1
20<35	0	•	•	•	7	6
10<20	0	•	•	2	18	9
6<10	•	•	2	5	10	3
3<6	•	1	1	3	2	•
1.5<3	0	•	0	•	0	0
0<1.5	1	1	•	•	0	0

2445

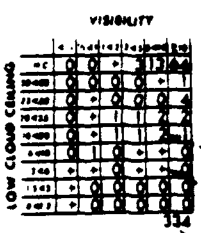
St. Paul

VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	1	14	8
50<80	•	•	0	•	•	•
35<50	•	0	0	0	2	2
20<35	0	0	•	•	9	4
10<20	•	•	•	2	17	4
6<10	0	•	1	3	8	1
3<6	1	1	3	4	3	1
1.5<3	•	1	1	•	•	0
0<1.5	5	1	•	•	•	0

4060

Legend **Low cloud ceiling/visibility**



Percent frequency of simultaneous occurrence of specified low cloud ceilings (hundreds of feet) and visibilities (nautical miles).

Low cloud ceiling heights are estimated from the height of low clouds (h) when low cloud amount (N_h) is ≥5/8.

Obscurations are included under ceiling "0 <1.5"

"N C" (no ceiling) includes bases of clouds ≥8000 feet as well as occurrences of N_h <5/8.

(2% of all observations reported ceiling ≥1000 but <2000 feet simultaneously with visibility ≥5 but <10 nautical miles.)

• indicates <.5% but >0.

Number of observations

Figure 2.6-27. Histograms of low ceilings and visibility correlations for selected stations.

Gambell

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	0	•	0	•	3	14
50<80	•	0	0	0	•	1
35<50	0	0	0	0	•	2
20<35	0	0	0	•	5	19
10<20	0	•	•	3	13	12
6<10	0	•	2	7	8	1
3<6	0	•	1	1	2	•
1.5<3	0	0	•	0	0	0
0<1.5	1	1	•	•	•	0

1237

Northeast Cape

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	•	5	12
50<80	0	0	0	0	•	•
35<50	0	0	0	0	1	2
20<35	0	•	•	1	15	17
10<20	•	•	1	5	14	9
6<10	•	•	1	3	4	1
3<6	•	•	1	1	•	•
1.5<3	0	•	0	0	•	0
0<1.5	1	1	1	•	0	0

2506

OCTOBER

Cape Romanzof

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	0	•	•	1	13	19
50<80	0	•	•	•	1	1
35<50	0	•	0	•	2	2
20<35	•	•	•	1	11	6
10<20	•	1	1	3	14	5
6<10	•	1	1	3	5	1
3<6	•	•	1	2	1	•
1.5<3	0	0	0	•	0	0
0<1.5	1	2	1	•	0	0

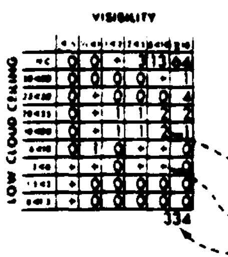
2454

St. Paul

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	0	0	•	1	19	7
50<80	0	0	0	0	1	•
35<50	0	•	0	0	2	1
20<35	0	•	•	1	14	6
10<20	•	•	•	4	24	4
6<10	0	•	1	3	5	1
3<6	•	•	2	1	1	•
1.5<3	•	•	•	•	•	0
0<1.5	1	•	•	•	0	0

4214

Legend **Low cloud ceiling/visibility**



Percent frequency of simultaneous occurrence of specified low cloud ceilings (hundreds of feet) and visibilities (nautical miles).

Low cloud ceiling heights are estimated from the height of low clouds (h) when low cloud amount (N_h) is ≥5/8.

Obscurations are included under ceiling 0 <1.5".

"N C" (no ceiling) includes bases of clouds ≥8000 feet as well as occurrences of N_h <5/8.

(2% of all observations reported ceiling ≥1000 but <2000 feet simultaneously with visibility ≥5 but <10 nautical miles.)

• indicates <5% but >0.

Number of observations.

Figure 2.6-28. Histograms of low ceiling and visibility correlations for selected stations.

Gambell

LOW CLOUD CEILING / VISIBILITY

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	•	4	7
50<80	0	0	0	•	1	1
35<50	0	0	0	•	1	1
20<35	•	0	•	1	7	8
10<20	1	1	2	6	14	9
6<10	•	1	3	4	8	4
3<6	1	1	1	1	1	•
1.5<3	•	•	•	0	•	0
0<1.5	5	2	1	•	•	0

1196

Northeast Cape

LOW CLOUD CEILING / VISIBILITY

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	1	8	10
50<80	0	•	0	•	•	•
35<50	0	•	0	•	•	•
20<35	•	•	1	3	13	6
10<20	•	1	3	9	17	3
6<10	•	•	2	3	3	1
3<6	•	•	•	1	1	•
1.5<3	0	0	0	0	•	0
0<1.5	4	3	2	•	•	0

2347

NOVEMBER

Cape Romanzof

LOW CLOUD CEILING / VISIBILITY

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	1	•	2	17	16
50<80	•	•	•	•	1	1
35<50	•	•	•	1	2	1
20<35	•	1	•	2	13	4
10<20	•	1	1	4	11	2
6<10	•	1	1	3	3	1
3<6	•	1	•	1	1	•
1.5<3	•	0	0	0	0	0
0<1.5	4	2	1	•	•	0

2331

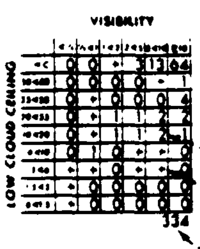
St. Paul

LOW CLOUD CEILING / VISIBILITY

	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	0	•	1	21	7
50<80	0	0	0	0	1	•
35<50	0	0	0	•	2	1
20<35	•	•	•	1	12	5
10<20	•	•	1	6	21	3
6<10	•	•	1	4	4	•
3<6	•	1	1	1	1	•
1.5<3	•	•	•	•	•	0
0<1.5	1	1	1	•	•	0

4200

Legend **Low cloud ceiling/visibility**



Percent frequency of simultaneous occurrence of specified low cloud ceilings (hundreds of feet) and visibilities (nautical miles)

Low cloud ceiling heights are estimated from the height of low clouds (h) when low cloud amount (N_h) is ≥5/8

Obscurations are included under ceiling 0 <1.5

N C (no ceiling) includes bases of clouds ≥8000 feet as well as occurrences of N_h <5/8.

(2% of all observations reported ceiling ≥1000 but <2000 feet simultaneously with visibility ≥5 but <10 nautical miles.)

• indicates <5% but >0.

Number of observations.

Figure 2.6-29. Histograms of low ceilings and visibility correlations for selected stations.

Gambell

LOW CLOUD CEILING \ VISIBILITY	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	0	0	•	2	6	10
50<80	0	0	0	0	1	1
35<50	0	•	0	•	1	1
20<35	•	•	1	1	5	3
10<20	1	2	4	9	14	7
6<10	1	2	3	5	4	1
3<6	•	1	•	1	1	0
1.5<3	0	•	0	0	0	0
0<1.5	7	3	1	•	•	0

1236

Northeast Cape

LOW CLOUD CEILING \ VISIBILITY	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	3	14	31
50<80	•	0	0	0	•	•
35<50	0	•	•	0	•	•
20<35	0	•	•	2	5	1
10<20	•	1	4	8	11	3
6<10	•	•	1	3	2	•
3<6	•	•	•	•	•	•
1.5<3	0	0	0	•	•	0
0<1.5	3	2	2	•	0	0

2299

DECEMBER

Cape Romanzof

LOW CLOUD CEILING \ VISIBILITY	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	1	1	1	5	25	18
50<80	•	•	•	•	1	1
35<50	•	•	•	•	1	1
20<35	•	•	•	2	6	1
10<20	1	1	1	4	9	1
6<10	•	1	1	3	3	•
3<6	•	•	1	1	1	0
1.5<3	0	0	0	0	0	0
0<1.5	3	2	1	•	0	0

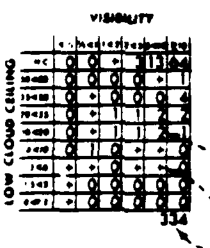
2344

St. Paul

LOW CLOUD CEILING \ VISIBILITY	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	•	•	•	1	18	6
50<80	0	0	•	0	1	•
35<50	•	•	•	•	2	2
20<35	1	1	1	2	16	4
10<20	1	1	1	6	19	2
6<10	•	•	1	3	3	•
3<6	•	1	1	2	1	0
1.5<3	•	•	•	•	0	0
0<1.5	2	1	•	•	0	0

4251

Legend **Low cloud ceiling/visibility**



Percent frequency of simultaneous occurrence of specified low cloud ceilings (hundreds of feet) and visibilities (nautical miles).

Low cloud ceiling heights are estimated from the height of low clouds (h) when low cloud amount (N_h) is ≥5/8.

Obscurations are included under ceiling 0 <1.5"

"N C" (no ceiling) includes bases of clouds ≥8000 feet as well as occurrences of N_h <5/8.

(2% of all observations reported ceiling ≥1000 but <2000 feet simultaneously with visibility ≥5 but <10 nautical miles.)

• indicates <5% but >0.

Number of observations.

Figure 2.6-30. Histograms of low ceilings and visibility correlations for selected stations.

In addition to wind, the storms tend to produce considerable clouds and precipitation. It is not uncommon to have low ceilings and visibilities, rain, drizzle, and fog even though strong winds are occurring. This is mentioned because in other areas, fog is correlated to calm or light wind conditions. See Figures 2.6-19 through 2.6-30 depicting frequencies of low ceilings and visibilities.

Another major atmospheric event occurs when strong pressure gradients form over the area as a result of low pressure in the Gulf of Alaska and high pressure over central and northern Alaska, and frequently eastern Siberia. This atmospheric pressure pattern frequently causes outbreaks of very cold air from Alaska, Siberia, and the Arctic Ocean. Strong north to northeast winds of 30 kts with temperatures -18°C (0°F) occur over the Bering Sea causing the ice pack to move southward and westward through the combined effects of wind drag and freezing of new ice at both windward and leeward ends of the ice pack. These conditions also cause thickening and hardening of the ice, and strong convergence of ice in some areas. Beyond the ice edge, ocean waves develop and superstructure icing conditions exist.

Another common condition occurs in July and August when the pressure gradient is very weak and winds are light. When this occurs, vast areas of low stratus and fog form over the Bering Sea. These conditions may exist for weeks making low level flying difficult if not impossible. For additional information, see Section 6.0.

2.7 Sea Ice

Sea ice is a major part of the physical geography of the Bering Sea. On severe ice years, it can extend southward past the Pribilofs and into all of Bristol Bay. The leading edge of the ice pack varies considerably from time to time and the character of the ice pack also varies considerably. At times, the ice pack can be transited by ordinary sea going vessels that are not specifically designed to resist ice forces. At other times, because of ice extent, ice character, and convergent conditions, only specifically designed ice breakers can move within the ice pack. This does not necessarily mean that it is unsafe for non-icebreakers, only that there may be times when no movement is possible. It follows also that some boats and small ships not specifically designed for ice could sustain serious structural damage. No specific knowledge is available on the subject of ice damage in the Bering Sea; however, boats and small ships have transited Cook Inlet for at least two decades in heavy ice conditions (to 0.8 m thick) with no known losses or reported damage.

Both the Bering Sea and Cook Inlet ice packs are comprised of first year ice except for occasional pieces of multiyear ice in the Northern Bering (north of St. Lawrence Island). The maximum thicknesses appear to be similar except that the shorefast ice in the Bering Sea is much thicker, whereas shorefast ice in Cook Inlet is almost non-existent because of the extreme tides. Little concrete knowledge of the navigability of the Bering Sea ice pack can be compiled until ships begin to routinely penetrate the pack and/or specific studies are made. See Section 7.0 for a full discussion of Bering Sea ice, and Section 8.0 for a full discussion of ship operations in first year ice. See Figure 2.7-1 for ice edge and coverage.

2.8 Rivers

Only one river empties directly into the Bering Sea Atlas Area, however, that river, the Yukon, is large with a maximum flow of close to one million cubic feet per second (cfs) which may occur during May or June. The summer flow is quite turbid. The winter

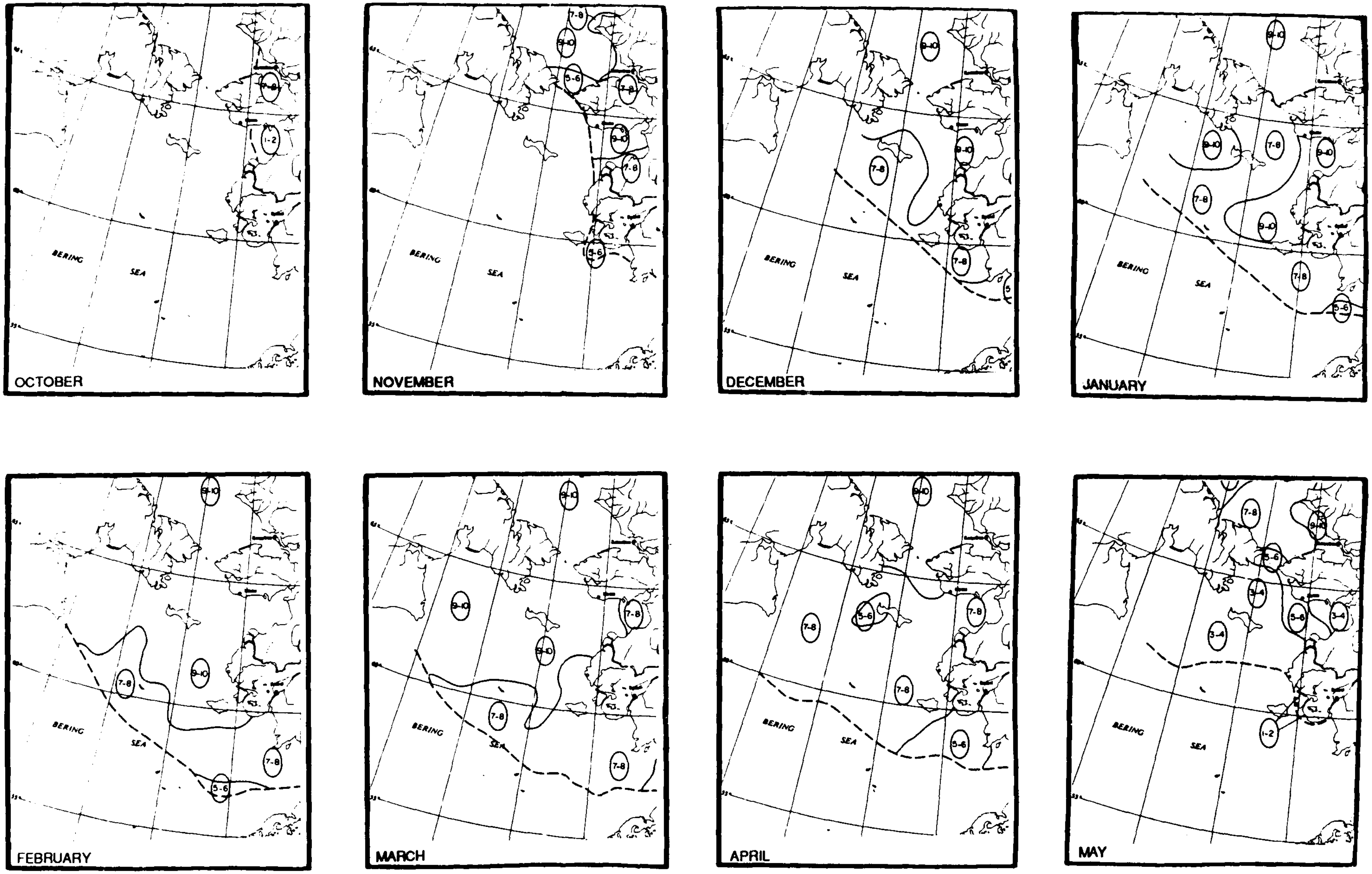


Figure 2.7-1. Dashed lines indicate the the most probable position of the ice pack edge. The numbers in the ellipses indicate the most probably ice coverage in tenths (LaBelle and Wise, 1983).

flow is much less turbid. The water, after leaving the Yukon flows mostly northward and eastward increasing the turbidity of Norton Sound.

The Kuskokwim River is a river of significant size which empties into the Bering Sea, but not directly into the Atlas area. It too is turbid during the summer, and the area south of Nunivak Island may be affected.

For additional information, see Section 3.4.

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3.0 FACTORS AFFECTING OIL SPILL TRANSPORT

3.1 Wind Driven Currents

Wind driven currents are the prime factor in oil spill transport. Wind driven currents may be a vector summation of all currents in a column of water affected by the wind (the boundary layer), or the wind driven current may be the current at the very top of the ocean (5 cm or less). This shallow current we call "wind drift" to differentiate it from other currents. Wind drift is the most important factor when considering oil spill movement. The wind drift is usually estimated to be 3 percent of the wind speed and moves in a direction 30 degrees to the right of the wind direction (Pease, 1987). See Section 4.1 Net Surface Currents, and Sections 6.1 for a full discussion of wind driven currents.

3.2 Tidal Currents

Tidal currents have a significant affect on oil spill trajectories over a short period of time (12 - 24 hours) and are particularly good predictors if surface winds are light. Because tidal action tends to be oscillatory or elliptical (Figure 2.4-4), in open water, the tidal transport vectors tends to indicate little movement of the oil or any surface particle during complete tidal cycles which, in the Bering, may be either 12 or 24 hours (approximately). Even during the short term, wind drag can significantly affect the tidal induced trajectory. The wind can cause a surface current of 2 to 5 percent of the wind speed (Pease, 1987). The average speed of the tidal current in open water is probably near 30 cm/sec. If we assume a 3 percent wind drag, an opposing wind of 19 kts would balance the tidal affect. A complimentary wind would double the tidal effect, etc. At any rate, wind is the most significant long term predictor. See Section 5.2.2 for more detailed information about Bering Sea tides and see Section 6.1 about wind and wind driven currents.

3.3 General Circulation

See Sections 2.3 and 5.2.1.

3.4 River Discharge

The Yukon River is the only river with significant discharge directly into the Bering Sea Atlas area and its discharge varies from one half million to one million cubic feet per sec (cfs) at the peak flow period during the latter part of May or early June. From the first part of December through April, maximum flow is less then 60,000 cfs (Chapman, 1982). During the summer months, the Yukon River water is quite turbid and satellite photographs show bands of turbid water extending northward and eastward into Norton Sound (Feeley *et al*., 1980).

The Kuskokwim River is also turbid and is close enough to the Atlas area that the area south of Nunivak Island may be affected. No streamflow measurements are available close to the coast, but using streamflow measurements inland, and ratio of streamflow to drainage area, it appears that maximum flow in May varies between 250,000 cfs and 63,000 cfs. From December through most of April, maximum flow is less than 25,000 cfs (Chapman, 1982).

Both rivers are turbid in the summer and much less turbid in the winter. Fresh water and lower salinities tend to enhance the early development of ice near the mouths during the early winter. After the shore ice forms, over-ice flooding is unlikely because of the deep river channels, i.e., the ice does not freeze to the bottom thereby obstructing the channel. In summer, the current is strong enough that opposing wind drag would not be able to overcome river currents thereby precluding oil movement into the main channel areas. Before attempting navigation, even in small boats, it is recommended that appropriate NOAA navigational charts and United States Coast Pilot 9 be studied in addition to any local knowledge available.

3.5 Ice Movement and Coverage

If an oil spill occurs within an ice pack, it is reasonable to assume that the oil will move with the ice pack. There will also be spreading of the oil, as a function of viscosity, density, and composition of the oil, surface tension, etc. However, the prime "transporters" are wind and tides. The effect of tides for the short term are obvious. The ice moves generally with the tide with the movement being modified by wind drag forces and stress internal to the ice pack. Flows and ice chunks surrounded by water are essentially free of internal stress for movement calculations. For the long term, more than 24 hours, the tide becomes less of a factor because of oscillatory effects equating to little or no net transport. Consequently, the wind is the prime forcing element. Various studies have shown that the ice tends to move to an angle of 25-30 degrees to the right of the wind direction and at a speed of 2 to 5 percent of the wind speed, measured at a height of 10 m. For further discussion and references, see Sections 4.5, 5.7, 6.6 and 7.0.

3.6 Temperatures - Oceanographic and Atmospheric

Atmospheric temperatures vary considerably even though the Bering Sea has a dampening effect. The mean air temperature ranges from -18°C to +8°C. The extreme air temperatures range from -35°C to +14°C. See Figures 3.6-1 through 3.6-3 for monthly mean temperatures.

Oceanographic temperatures (sea surface temperatures - SST) are much more conservative. SST's range from 11°C to 3°C along the Aleutian Chain and from 5°C to -2°C in the northern Bering Sea. The changes reflect seasonal variations. SST's may vary as much as 2°C from their monthly mean. When ice is present, no significant variation occurs and the water temperature is

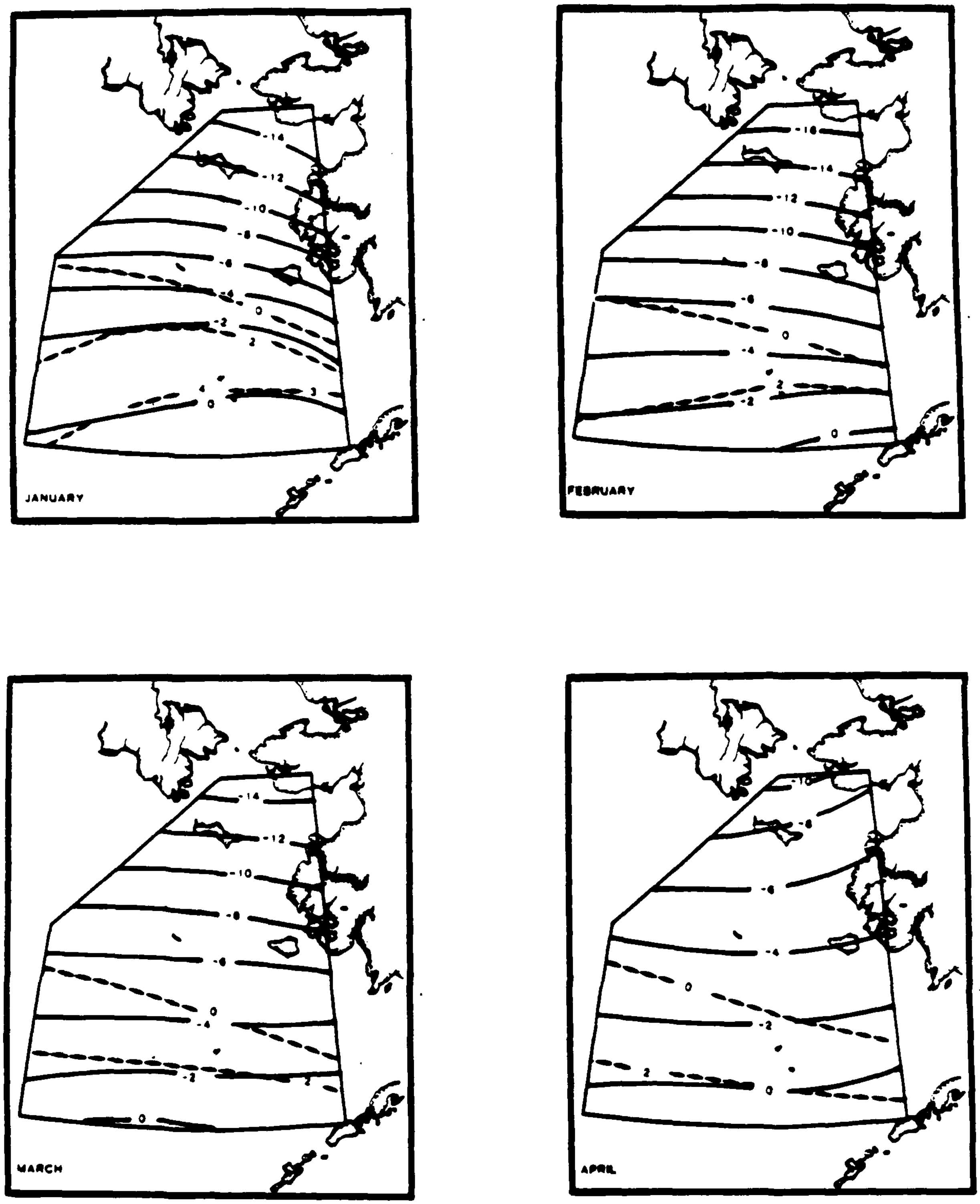


Figure 3.6-1. Mean monthly air temperatures (solid lines) and sea surface temperatures (dashed lines) in degrees Celsius. (Adapted from Brower et al., 1977)

Figure 3.6-2. Mean monthly air temperatures (solid lines) and sea surface temperatures (dashed lines) in degrees Celsius. (Adapted from Brower et al., 1977)

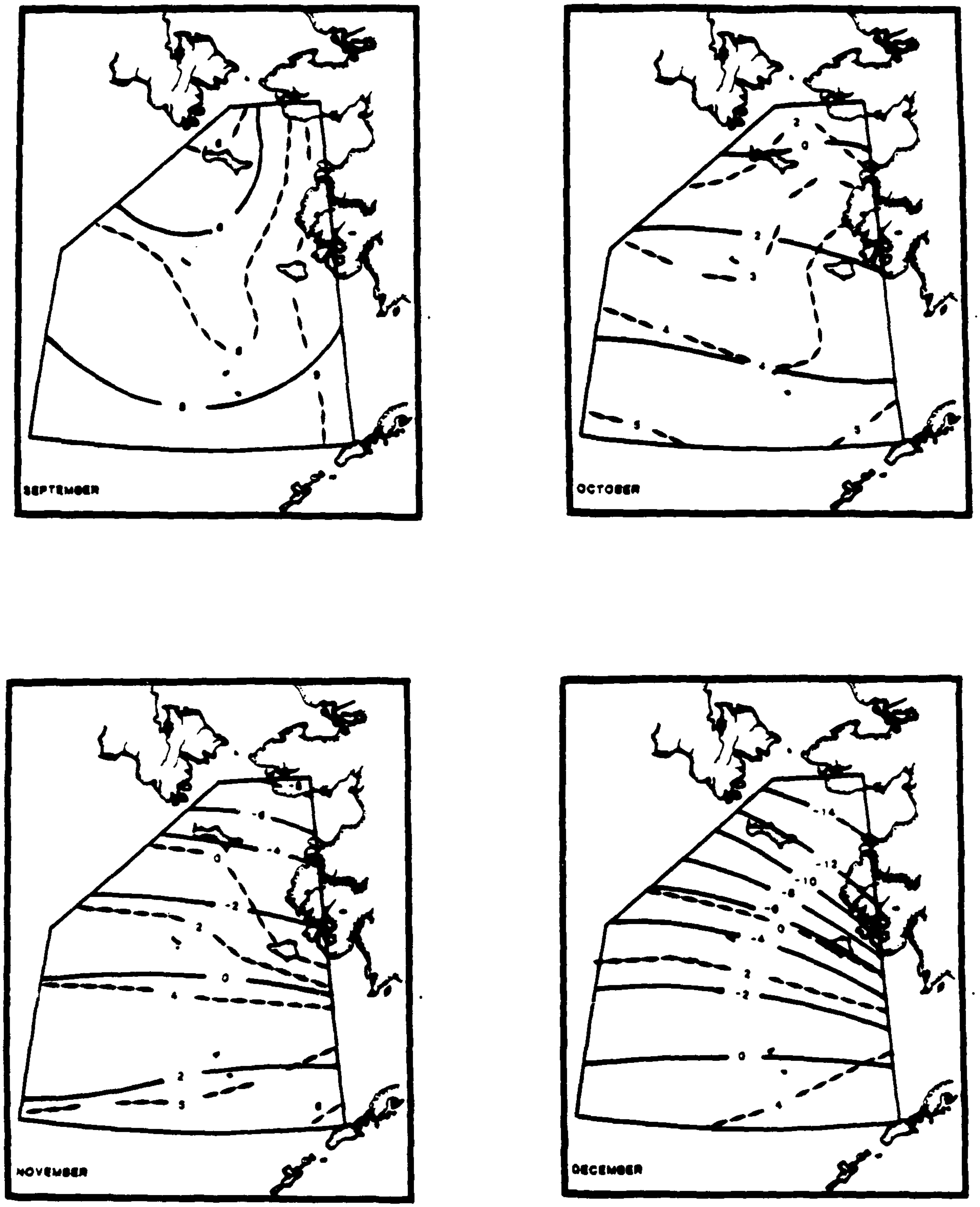


Figure 3.6-3. Mean monthly air temperatures (solid lines) and sea surface temperatures (dashed lines) in degrees Celsius. (Adapted from Brower et al., 1977)

approximately -1.8°C. See Sections 5.4 and 6.2 for additional information. See Figures 3.6-1 through 3.6-3 for monthly mean sea surface temperatures.

3.7 Storm Surges

If an oil spill occurs near low lying land, the oil could be spread over large land areas via the media of a storm surge. A storm surge may be simplistically defined as unusually high water and related flooding along a coast. The dynamic forces (wind, currents) that control the movement of oil over water is similar to those in a non-surge area. The primary difference is that these forces are now allowed to act over land because of the flooding. The coastline and low lying land between Kuskokwim Bay and the Yukon Delta is very susceptible to storm surges. Therefore, modelers and on-scene coordinators should be aware that the coastline does not necessarily mark the limit of oil movement. They should also be aware that even if given the height of the surge (to 12 ft), the penetration inland in most cases will not be known because of the lack of topographic definition in remote western Alaska. Further information is contained in Section 4.3, Chapter 4.0 (Factors Affecting Oil Spill Containment and Mitigation Efforts), Section 5.5, Chapter 5.0 (Oceanography), an extensive discussion in Section 6.7, Chapter 6.0 (Climatology and Meteorology), and a forecast procedure in Appendix B.

3.8 Bathymetry

The bathymetry of the Bering Sea can affect oil spill transport via the phenomena of storm surges and character of wind wave spectra (sea conditions). The former (surges) can cause the spread of oil beyond normal coastline boundaries. See Section 6.7 for a full discussion of storm surges. Varying wave forms caused by relatively shallow ocean depths can affect the horizontal and vertical displacement of oil but its affects may be insignificant or unpredictable. See Section 5.3 for a full discussion of sea conditions. Also see Figure 2.2-1.

3.9 Sea Conditions

Waves contribute significantly to the dispersion of oil droplets into the water as the oil spills age. The rate of dispersion is correlated to wave characteristics such as extent of whitecaps, plunging, breaking, currents, water densities, air-water density differences, etc. These types of wave characteristics and other dispersion parameters are beyond the scope of this atlas; however, the subject of sea conditions as normally considered is discussed extensively in Section 5.3. See Figures 3.9-1 through 3.9-6 for wave height and direction summaries.

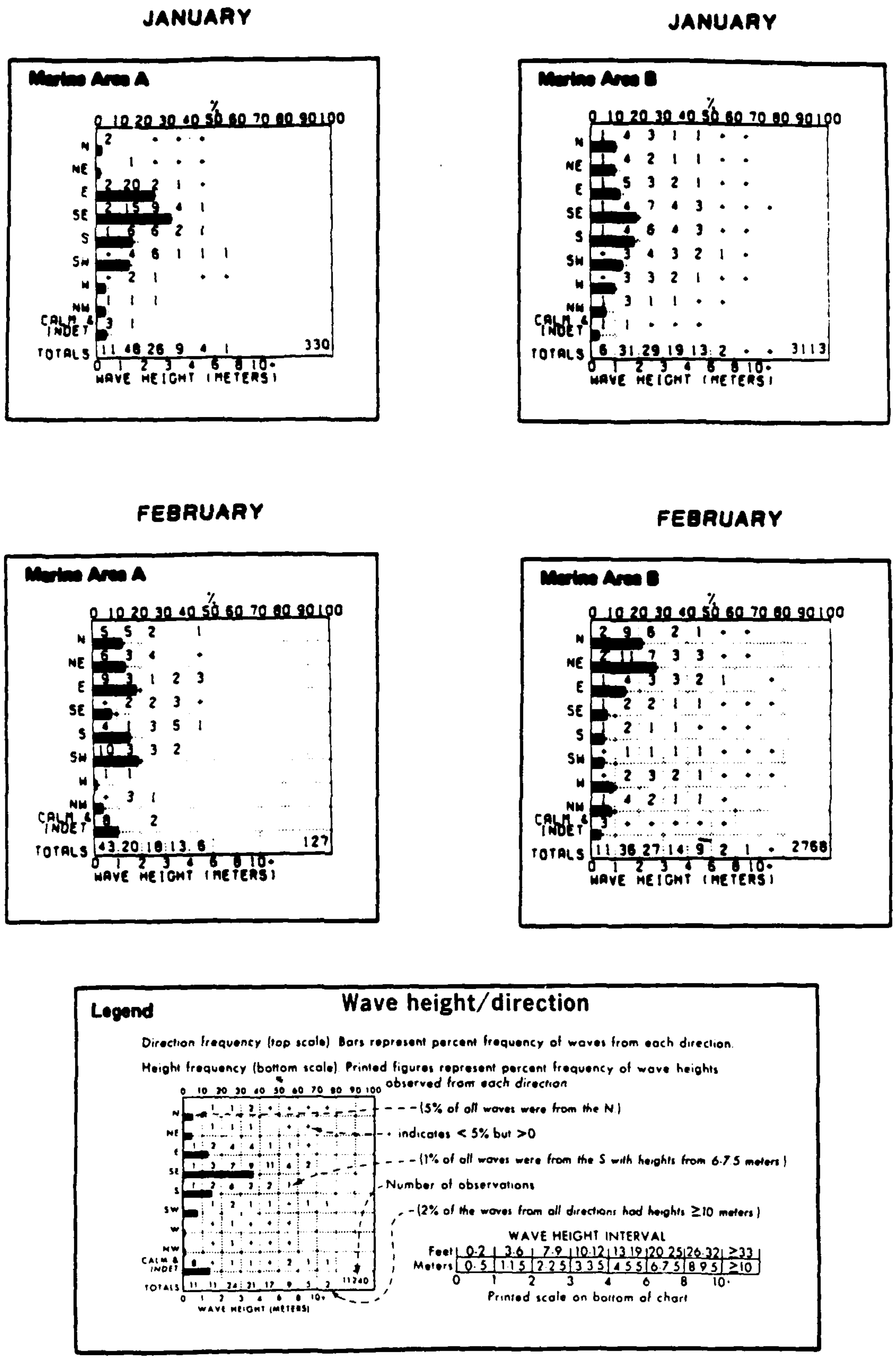


Figure 3.9-1 Wave height and direction summaries. Marine Area A correlates to the northern Bering Sea and Marine area B correlates to the southern Bering Sea. Because of data problems and sea ice variability these summaries should be used with caution. (Adapted from Brower et al., 1977)

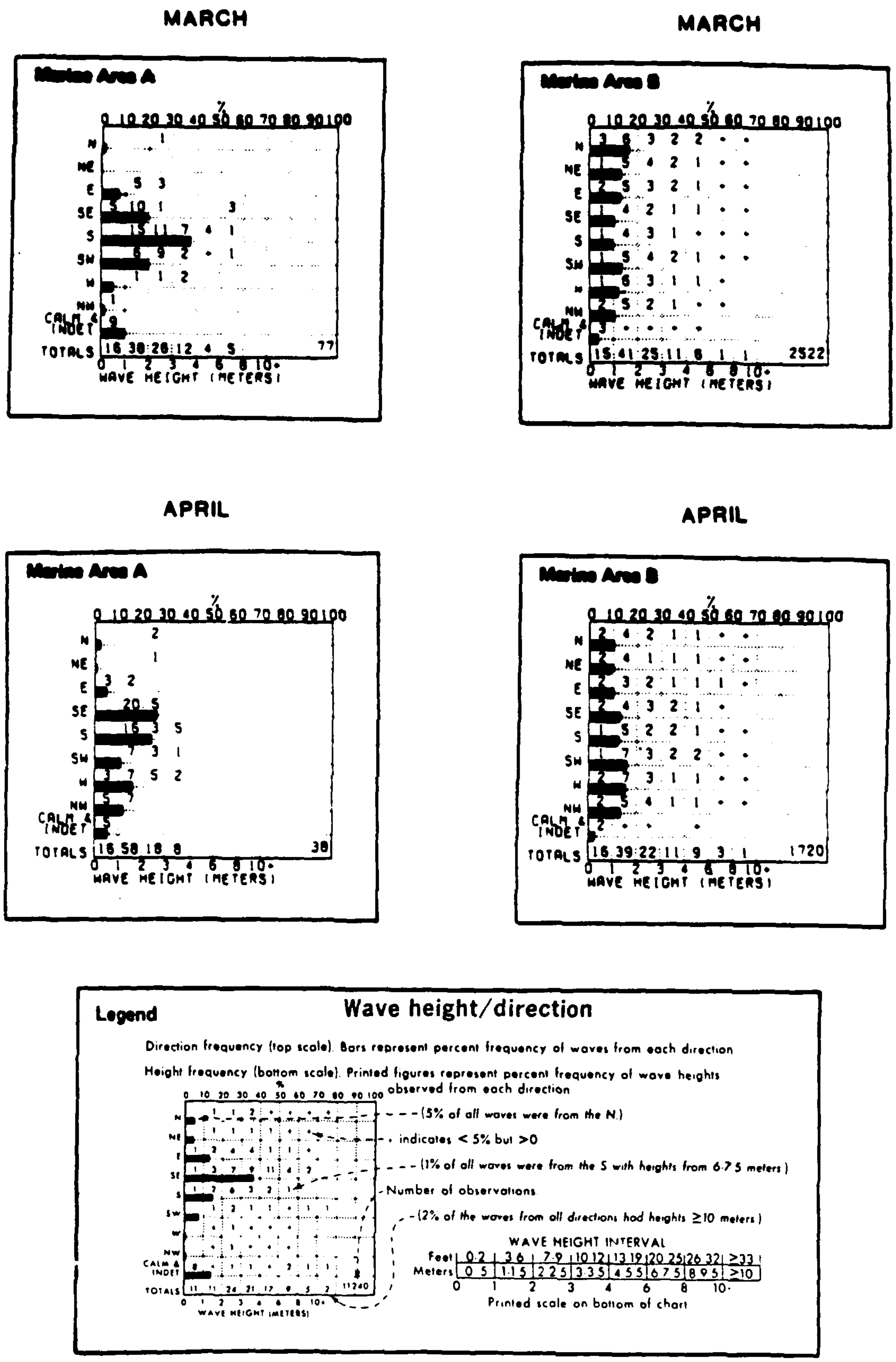


Figure 3.9-2. Wave height and direction summaries. Marine Area A correlates to the northern Bering Sea and Marine area B correlates to the southern Bering Sea. Because of data problems and sea ice variability these summaries should be used with caution. (Adapted from Brower et al., 1977)

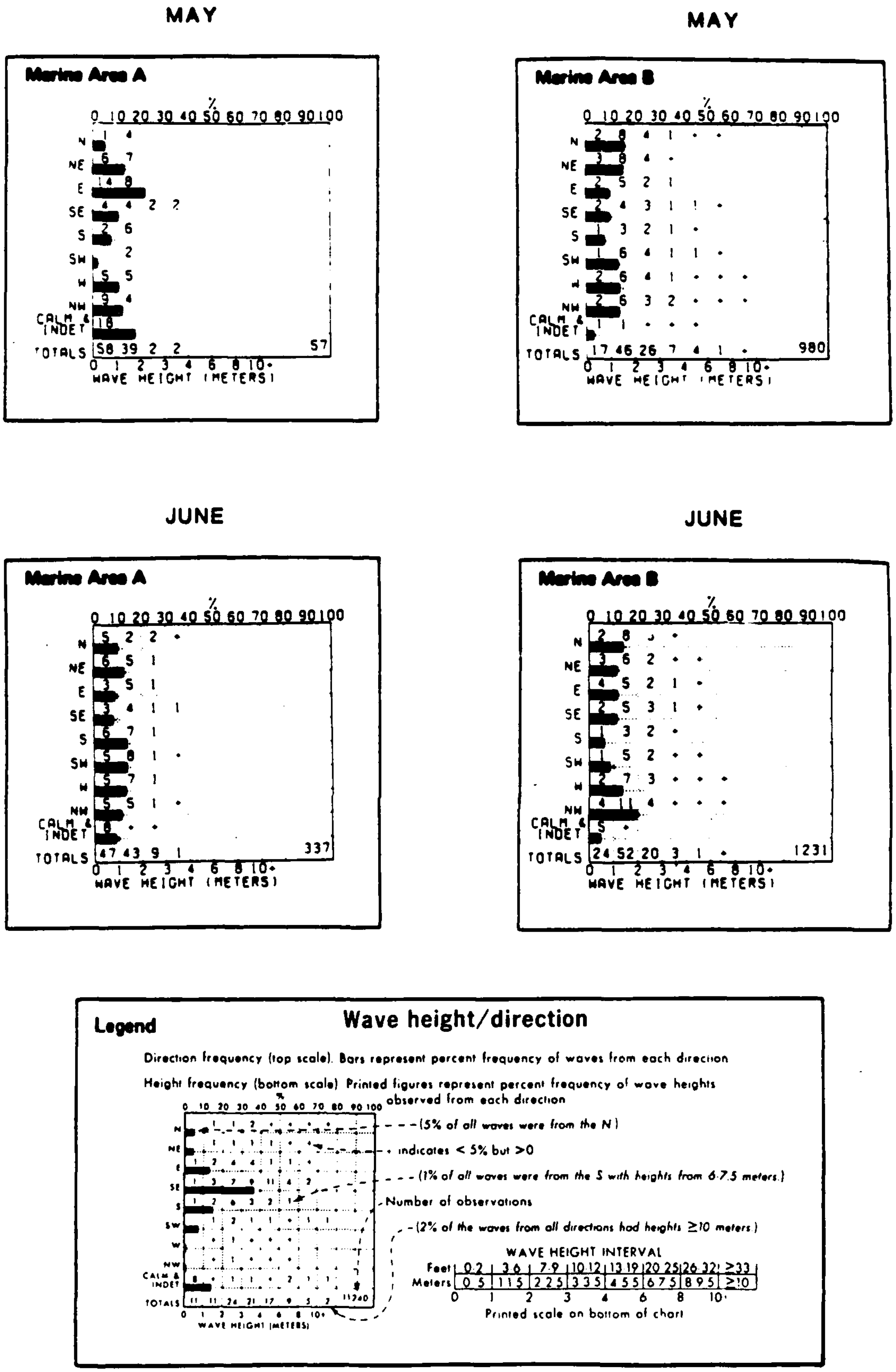
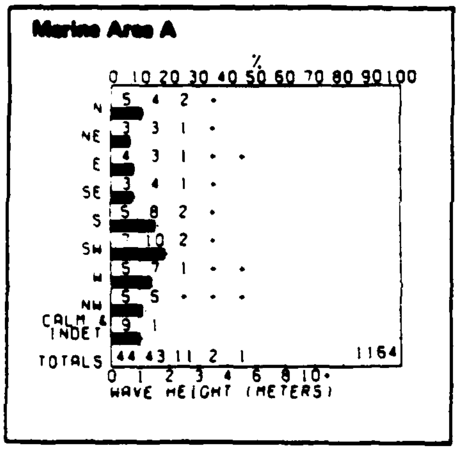


Figure 3.9-3.Wave height and direction summaries. Marine Area A correlates to the northern Bering Sea and Marine area B correlates to the southern Bering Sea. Because of data problems and sea ice variability these summaries should be used with caution. (Adapted from Brower et al., 1977)

JULY



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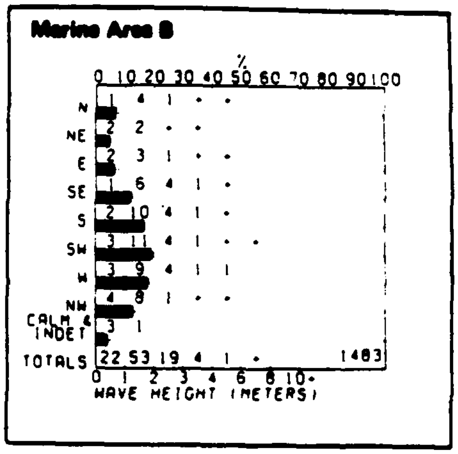
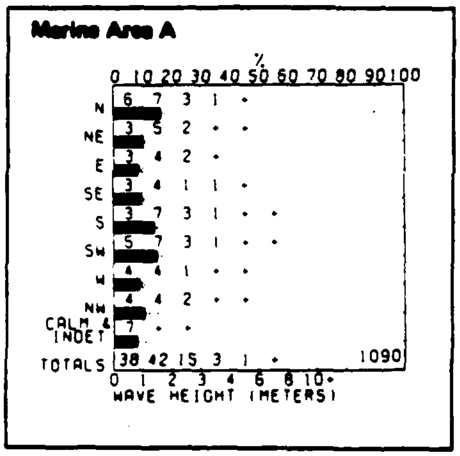


AUGUST



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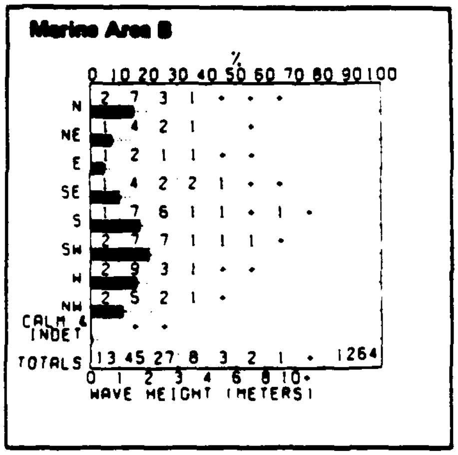


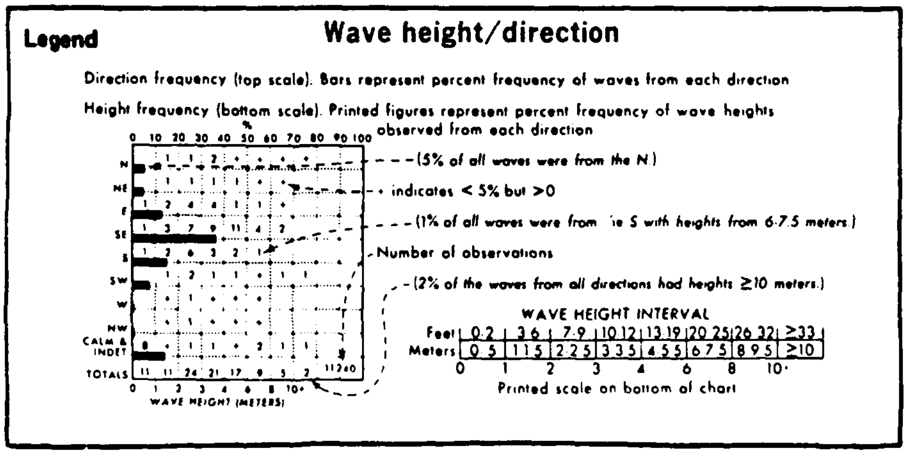
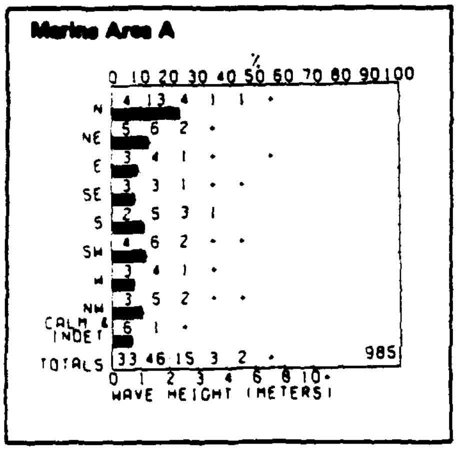


Figure 3.9-4. Wave height and direction summaries. Marine Area A correlates to the northern Bering Sea and Marine area B correlates to the southern Bering Sea. Because of data problems and sea ice variability these summaries should be used with caution. (Adapted from Brower et al., 1977)

SEPTEMBER



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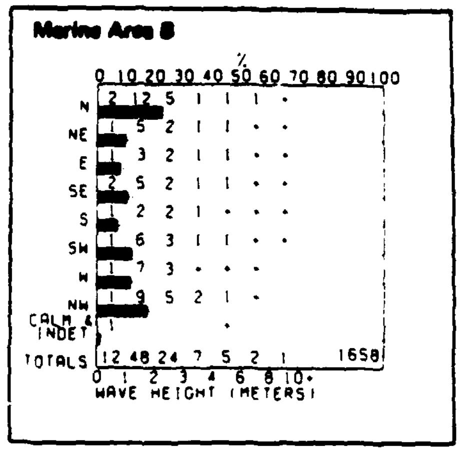
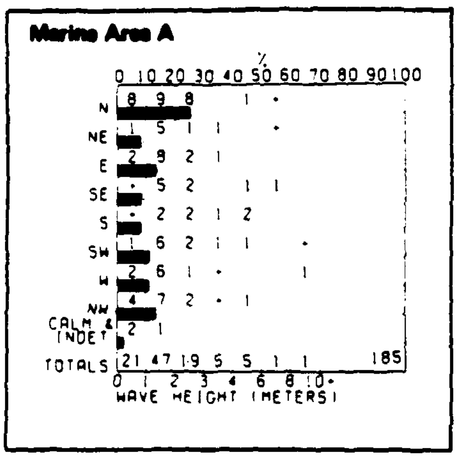


OCTOBER



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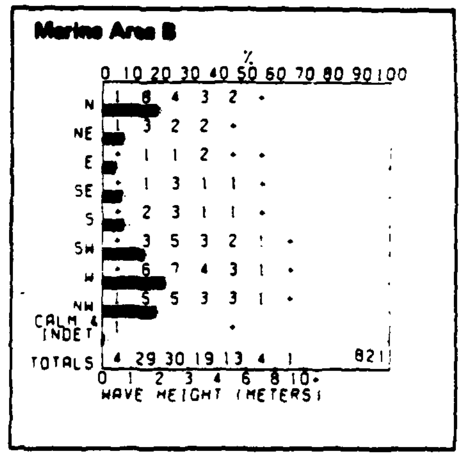


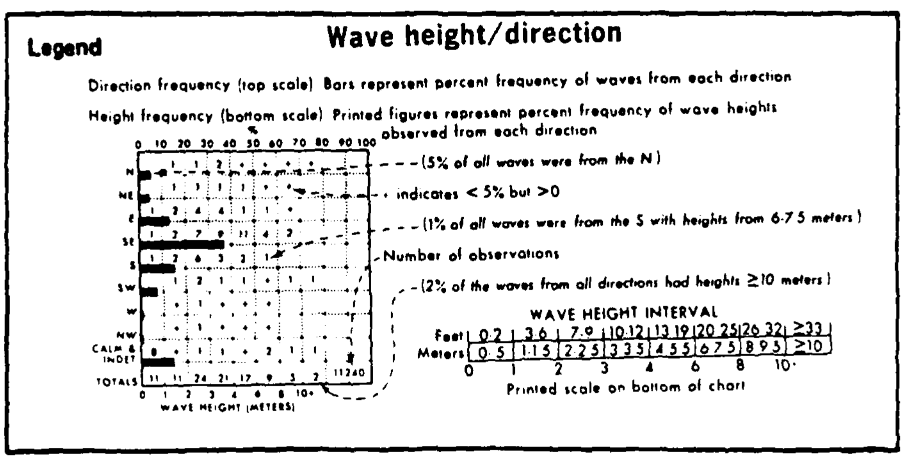


Figure 3.9-5.Wave height and direction summaries. Marine Area A correlates to the northern Bering Sea and Marine area B correlates to the southern Bering Sea. Because of data problems and sea ice variability these summaries should be used with caution. (Adapted from Brower et al., 1977)

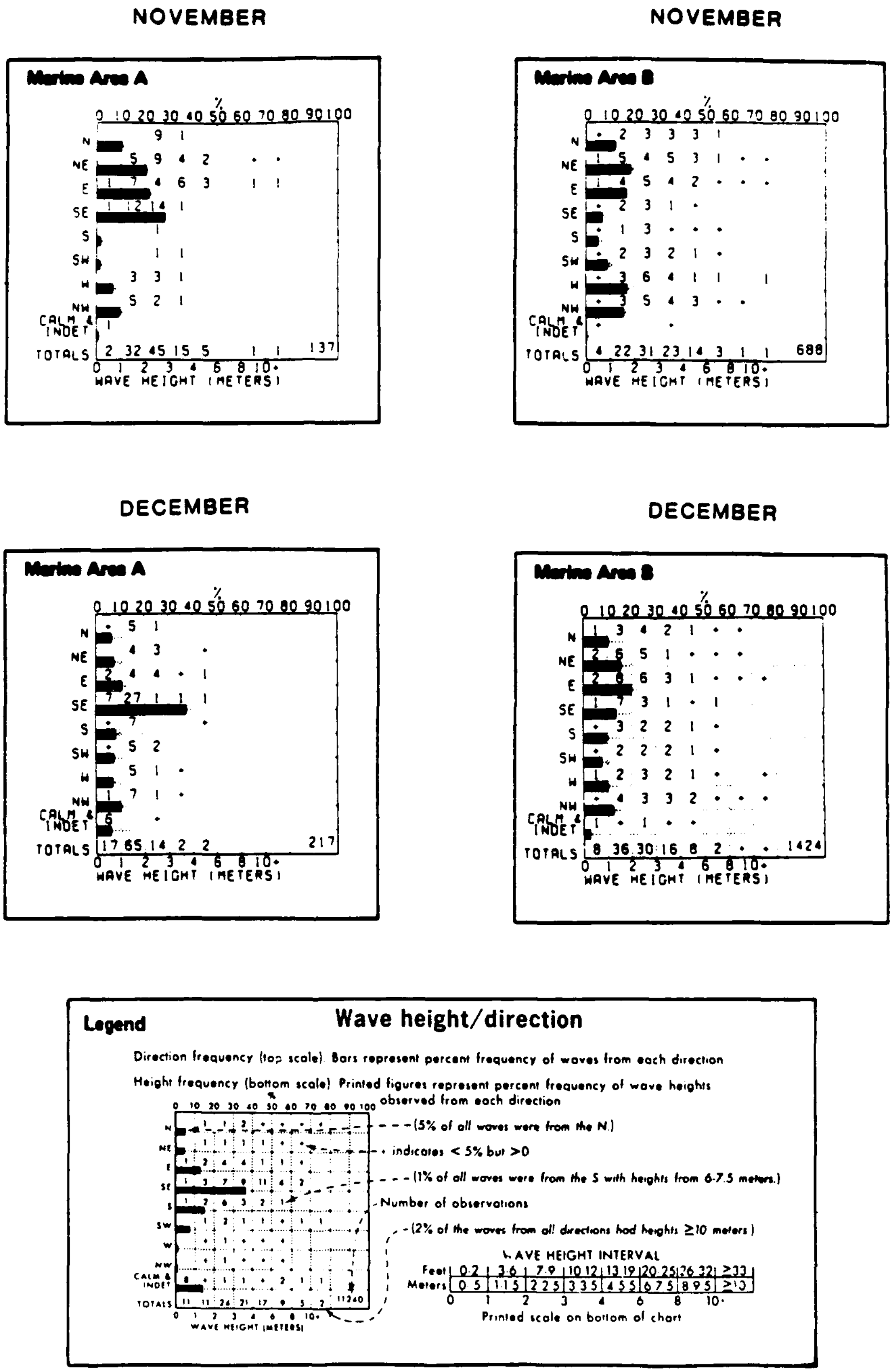


Figure 3.9-6.Wave height and direction summaries. Marine Area A correlates to the northern Bering Sea and Marine area B correlates to the southern Bering Sea. Because of data problems and sea ice variability these summaries should be used with caution. (Adapted from Brower et al., 1977)

4.0 FACTORS AFFECTING OIL SPILL CONTAINMENT OR MITIGATION EFFORTS

4.1 Net Surface Currents

The net surface current at any given time is the vectorial summation of wind driven currents, tidal currents, wave induced drift, and general circulation. The general circulation current is for all practical purposes overridden by wind and tidal current. Wave induced drift is a function of wind and related sea surface wave spectra and is usually included in the wind driven current vector. Thus wind driven currents and tidal currents are the prime components of net surface drift.

Many oceanographers consider the "surface current" to be the entire column of water affected by the wind (the boundary layer). Wind driven currents below the surface of the ocean veer to the right of the wind direction or to the right of the next highest current. Thus the net transport of water is about 45 degrees to the right of the wind drift (at the ocean's surface). This current when considered with the tidal current, most accurately depicts the net current in the boundary layer. Over a period of one or more tidal cycles, the tidal current can in many cases, be ignored because of its oscillatory nature.

The net current at the very top of the ocean, the wind drift, which occurs at the oil transport level, is the current of most importance. When combined with the tidal current, it most accurately depicts the "surface" current and velocity of oil movement. Again over a period of one or more tidal cycles, the tidal current can be ignored. The wind drift is usually estimated to be 3 percent of the wind speed and moves in a direction 30 degrees to the right of the measured 10-20 m wind direction. For additional discussion of wind driven currents, see Section 6.1.

4.2 Sea Conditions

Sea conditions normally refer to the shape of the ocean's surface as determined by one or more wind fields. A wind field generates a set of waves. When freshly generated, they are commonly referred to as wind waves, or "seas". If the wind field dies or moves, or if the waves leave the wind field area, the waves change character and begin to decay. These decaying waves are commonly referred to as "swells". With time, it is common that the swells will be subjected to another wind field. At that time, another set of waves (seas) will form on the swells. We now have what is frequently called seas and swells. For instance, the swell may be 1.5 m in height and the seas may be 0.5 m in height. The combination of seas and swells is frequently referred to as just plain "seas", sea conditions, or combined seas.

In addition to normal perceived "sea conditions", there are other factors affecting oil spill containment such as the vertical dispersion of oil droplets in the column and the horizontal displacement of oil unique to certain wave forms such as breaking and plunging waves. These types of unique wave forms are beyond the scope of this atlas; however, the subject of sea conditions as normally considered is discussed extensively in 5.3.

4.3 Storm Surges

If an oil spill occurs near low lying land, the oil could be spread over a large land area via the media of storm surge. A storm surge may be simplistically defined as unusually high water and related flooding along a coast, with the high water being caused by a storm and relatively small ocean depths offshore. The Bering Sea has both storms and small ocean depths. The probability of having a significant storm surge coincident with an oil spill is remote but marine accidents tend to be correlated with inclement weather and the possibility exists. If oil should be transported inland by the flooding surge waters, containment becomes very difficult. The coastline and low lying land between Kuskokwim Bay and the Yukon Delta is very susceptible to storm surges. In that area the surge flooding has been reported as far as 20 nmi from the outer coast. For further information on storm surges see Section 5.5, Section 6.7 and a forecast procedure in Appendix B.

4.4 Superstructure Icing

Superstructure icing is the freezing of liquid water on marine structures. Marine structures are defined as ships, boats, skimmers, booms or anything on or near the ocean that may be subject to freezing spray. Superstructure icing is most frequently caused by waves hitting the structure with the resultant spray subsequently freezing on the structure.

Superstructure icing occurs when very cold air and strong winds occur over open, and cold water. It can seriously affect the operations of marine structures. Ships to 200 feet in length can accumulate enough tons of ice to make them unstable. Ships or boats of 40 to 200 feet are most adversely affected by heavy seas whereas boats and equipment of less than 40 feet may actually fare better because the frequent washing by relatively warm ocean water may keep surfaces free of ice. Conversely, the smaller equipment may be adversely affected by short choppy seas, wherein some spray is generated, while the larger equipment is relatively unaffected. Various fishermen have described shelves of ice 4 to 6 feet wide forming to the vessel's hull while at anchor in large bays with strong winds. Given that superstructure icing conditions exist, the extent of icing is determined by the size and spray characteristics of the marine structures.

The greatest probability of superstructure icing occurs from December through March in the southern Bering Sea. For additional information on superstructure icing, see Section 5.6 under Oceanography, and for an even more extensive discussion of superstructure icing including a superstructure icing forecast method, see Section 6.4.

4.5 Sea Ice

Sea ice could be a major deterrent to oil spill containment and/or mitigation. It may be difficult, if not impossible, for equipment to function within the ice. It depends on the thickness of the ice and its character such as flow size, flows or rubble, consolidated rubble, and relative strength. On the other hand, the ice pack could beneficially restrict the movement of oil or other pollutants. The condition of ice convergence and divergence is also a factor and could inhibit or assist containment and mitigation efforts.

4.5.1 Ice Movement and Coverage

Shore ice begins to build in October in Norton Sound and in shallow bays from Cape Avinof northward. The ice pack builds rapidly southwestward with shore ice occurring as far southward as Bristol Bay by November. Maximum extent of the ice pack normally occurs in March with the leading edge along a line from southern Bristol Bay to 25 nmi north of St. Paul Island thence west-northwest. In April rapid retreat and/or disintegration begins and the area is mostly open water by June 1.

The ice pack normally moves from northeast to southwest; however, large storms entering the Bering Sea can cause large variations (anomalies) in both ice movement and ice coverage. Reynolds et al., 1985 deployed eight (8) ARGOS-tracked transponders (ice buoys) at approximately 61° N 170° W. They moved initially west-northwest to north of St. Matthew Island then southwest. In

1982 Reynolds and Pease (1984) deployed six (6) ARGOS Platforms in Norton Sound, generally south and southwest of Nome, and these platforms recorded very erratic tracks with one moving north and south several times through the Bering Strait. Another moving north and south, made several passes between the mainland and St. Lawrence Island. It is important to remember that there are at times huge variations between climatological values and real time values. Also, climatological and actual advance of the ice edge is a function of pack movement plus freezing in advance of the pack. Conversely ice retreat is a function of ice movement and ice melt. A general rule is that ice tends to move at an angle of 25-30 degrees to the right of the wind direction and at a speed of 2 to 5 percent of the wind speed at 10 m.

4.5.2 Ice Character

Ice varies considerably in character which can affect the mobility of vessels and equipment operating in the ice. The ice can be in flows of varying sizes and thicknesses, or it can be a multitude of ice bits along with frazil (ice slush). Bits and slush, sometimes covered with snow are generally known as rubble. Rubble can be loose or consolidated (frozen together) and is of varying thickness. Also a variability of both flows and rubble is hardness. Hardness is a function of temperature - the colder the temperatures, the harder the ice. In addition, cold temperatures consolidate rubble and rubble to large flows making operations most difficult. In short, cold thick flows, closely packed (convergent), are the most difficult of the ice characteristics for seaborne operations. For further discussions of sea ice, see Section 7.0.

4.6 Bathymetry

Bathymetry should have little unanticipated affects on marine operations. There are the normal problems of operating close ashore in shallow water. Elsewhere the continental shelf is relatively shallow but there is more than adequate water depth for ship operations, and the water depth is such that "deep water" wave spectra should be expected. The deep water wave spectra can be predicted using either the Hasselman or Bretschneider methods. See Section 5.3. Also see Figure 2.2-1.

4.7 Flying Conditions

Flying conditions can be difficult during storms, during periods with high pressure gradients, and during the summer months when extensive fog and low stratus form over the Bering Sea. The degree of difficulty can be increased when pilots and dispatchers are not familiar with the area. Local input is important. See Section 6.5 for a full discussion of flying conditions.

5.0 OCEANOGRAPHY

5.1 Bering Sea Overview

The Bering Sea differs from the north Pacific Ocean in several ways. Periods of swells in the Bering Sea, and wave heights in general, are less than in the Pacific Ocean (Brower et. al., 1977). The Aleutian Islands inhibit the propagation of long swells from the north Pacific and the proximity of Alaska and Siberia, as well as the Aleutians, reduce the wind fetch, all of which contribute to different wave conditions. This does not necessarily imply that sea conditions are less hazardous in the Bering Sea. Relatively high wave heights with short periods can be extremely rough for boats and small ships. In the Bering Sea, the fetch from southwest to northwest is quite long and the greatest potential for high seas is from those directions. However, climatologically, storms do not usually position themselves to cause long wind fetches from westerly directions.

The Bering Sea also differs from the Pacific in the large extent of its continental shelf. The shelf in itself does little to modify sea surface conditions. Its major feature is that it attracts considerable traffic, mostly fishing boats and equipment relating to fossil fuel development. In spite of the continental shelf, the Bering Sea should still be considered a deep water sea for purposes of modelling or forecasting oceanic conditions-such as sea conditions (waves).

Another feature of the Bering Sea is its ice cover during the winter. The ice itself can inhibit navigation, but on the other hand, it can cause lower wave heights because of reduced fetch, lower superstructure icing because of lower wave heights, and lower temperatures as the ice pack begins to act similar to a land mass with its lesser heat flux and greater radiation characteristics.

5.2 Currents

5.2.1 General Circulation

The general circulations of the Bering Sea for winter and summer are depicted in Figures 2.3-1 and 2.3-2. General circulation arrows, or vectors, attempt to depict the net transport of water in a column of water over a long period of time (years). The major long term energy source for these currents is wind, therefore climatological winds are best correlated to general circulation. Day-to-day real time winds can generate currents within the ocean from the surface to a considerable depth (the boundary layer) which completely override the general circulation, or climatological currents. Because the climatological wind driven currents within the boundary layer eventually prevail, they are used to depict with reasonable accuracy the net transport of water in the entire water column. The boundary layer is defined as that portion of the vertical water column affected by the wind. To further complicate the subject, the term "surface currents", as used by many oceanographers, depicts the net current in the boundary layer and the thickness of the boundary layer varies with wind speed and duration, among other variables. The term "wind drift" is frequently used to depict the direction and speed of water molecules (current) very close to the ocean's surface. Wind drift is, in effect, the current of most importance to oil spill trajectory modelers and forecasters. In this atlas, the terms surface currents, or wind driven currents, relate most closely to wind drift.

Figures 2.3-1 and 2.3-2 depict an estimate of general circulation in the Bering Sea. Although general knowledge of portions of the general circulation have been known for 300 years, systematic studies of the flow employing direct currents measurements began only in 1964 (Coachman and Aagaard, 1966). Figures 5.2.1-1 and 5.2.1-2 depict measurements made in the northern Bering Sea. Both figures indicate some measurements in substantial

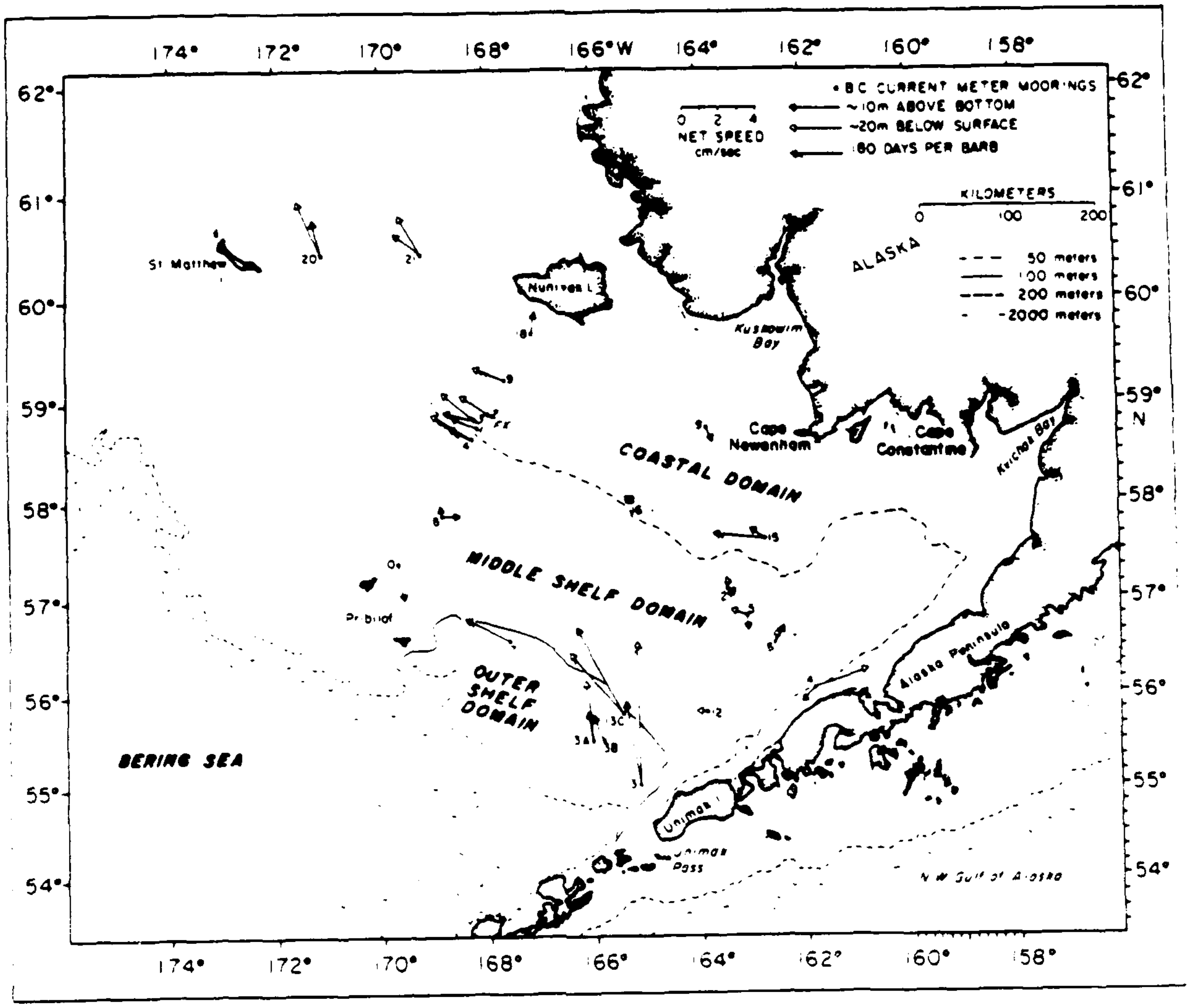


Figure 5.2.1-1. Observed vector mean currents from moored buoys (Kinder and Schumacher, 1981).

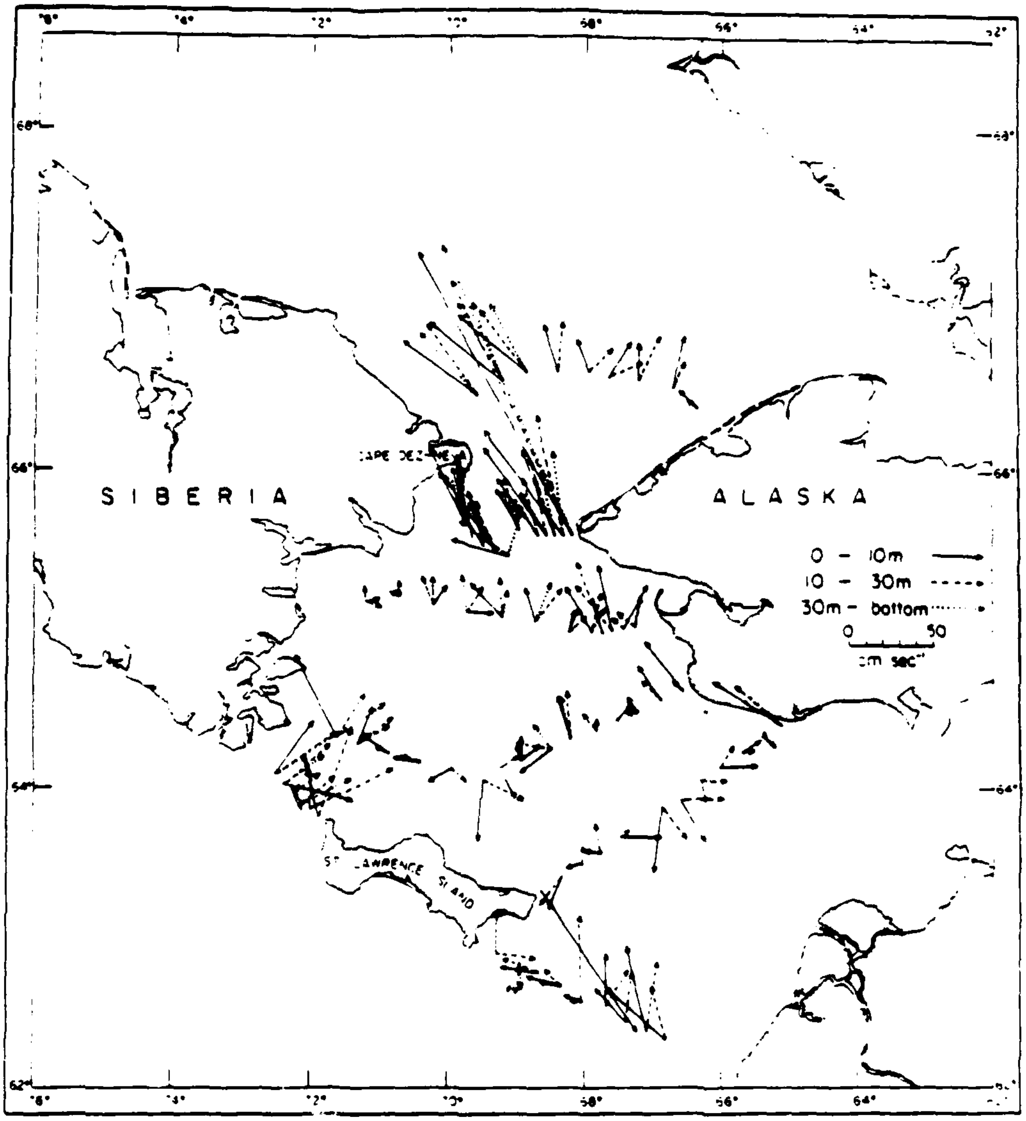


Figure 5.2.1-2. Currents averaged over three layers measured by the Staten Island from July 9-19, 1968. (Coachman, et al., 1975).

disagreement with the general circulation of Figures 2.3-1 and 2.3-2. The disagreements do not materially subtract from the general circulation concept for reasons stated previously.

In summary, general circulation is not significantly useful for modeling and forecasting of oil spill trajectories - particularly for relatively short periods of time and/or where the general circulation is weak. Its prime value may be in resources at risk analyses.

5.2.2 Tidal Currents

Tidal currents in the Bering Sea have average velocities ranging from 26 cm/s to 52 cm/s except nearshore, in places, and the entrance to Hooper Bay (NOS, 1986; NOS, 1979). It is likely that strong tidal currents also flow into and out of other bays in western Alaska. The following is extracted from NOS, 1979 (U.S. Coast Pilot 9).

Currents - Strong tidal currents flow through the Aleutian Islands passes, setting into the Bering Sea on the flood and into the North Pacific Ocean on the ebb. Observed velocities have exceeded 8 knots in some of the passes, but the decrease is rapid once the passes are cleared. The tidal currents set N and S along the Bering coast and into and out of the various bays. The periodic tidal flow along the coast is completely masked at times by wind currents. In constricted bays, the currents may have considerable velocities. Tidal currents have an average velocity of 0.5 to 1 knots at the off-lying islands.

Pearson et al. (1980) reported the results of specific tide measurements. Figure 5.2.2-1 depicts tidal trajectories (excursions), current speed, and rotation of lunar (M_2) tides. The current speeds ranged from 10 to 30 cm/s. Figure 5.2.2-2

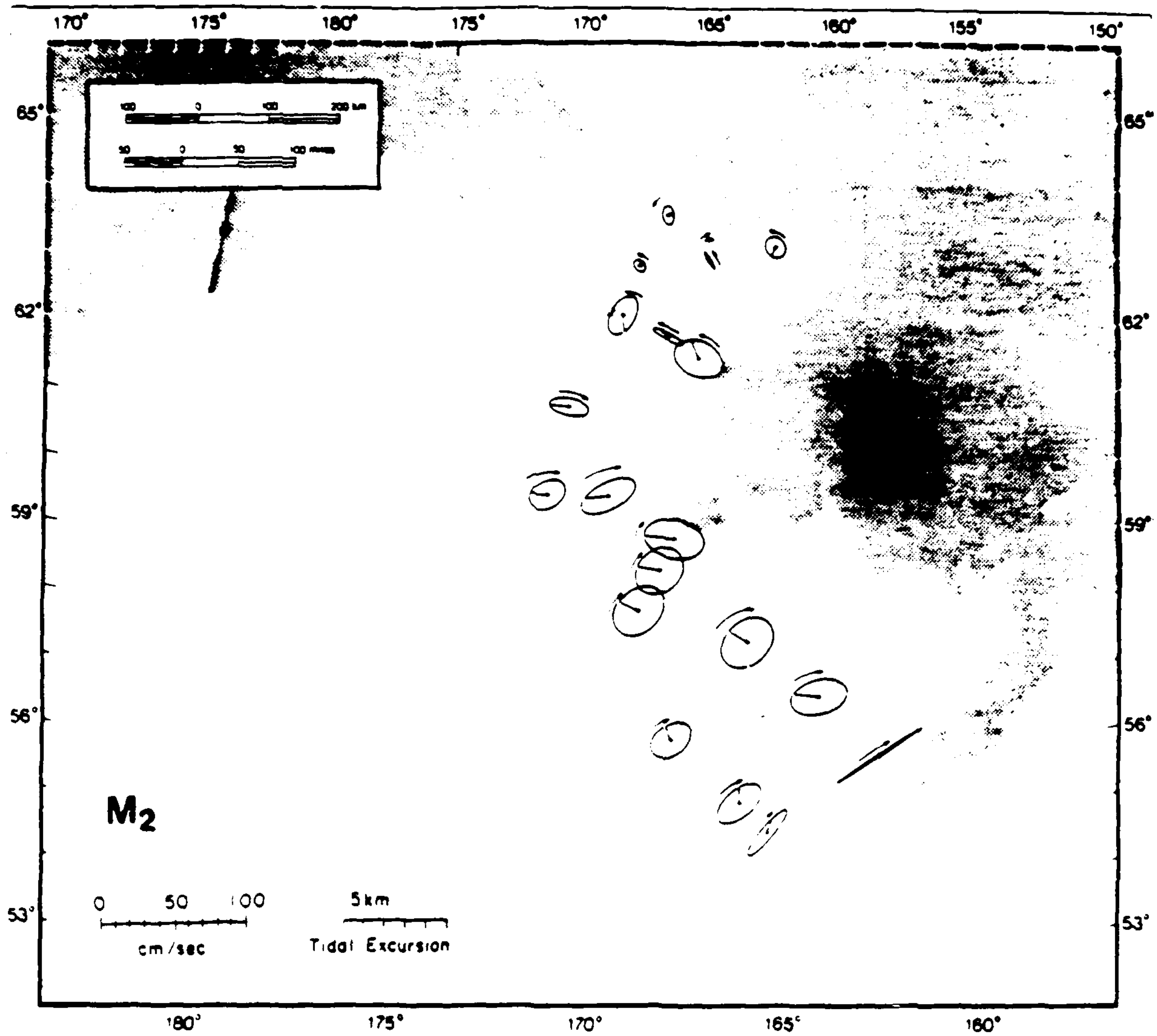


Figure 5.2.2-1.. Lunar (M_2) tidal current ellipses in the Bering Sea (from Pearson et al., 1980).

depicts the cotidal lines and Figure 5.2.2-3 depicts the corange lines (Pawlowski, 1987) and the areas of semi-diurnal, diurnal, and mixed tides. It is necessary to refer to the appropriate tide tables to determine whether the tidal change is diurnal or semi-diurnal in the mixed area.

5.2.3 Wind Driven Currents

There are two basic types of wind driven currents. One type is the current resulting from climatological winds (winds averaged over a long period of time). This current added to other currents induced by oceanic and atmospheric dynamics, such as baroclinicity, density differences, and atmospheric pressure, equate to a flow of water called general circulation. General circulation estimates are shown in Figures 2.3-1 and 2.3-2. General circulation is not a significant factor in oil spill trajectory modeling or forecasting, especially in the short term because the currents generated by winds during an oil spill episode override the general circulation currents. In addition the general circulation current reflects the net transport of water in the entire water column and is not representative of surface currents. See Section 6.1.2.

The other type of wind driven current is the real time current induced by real time winds. For oil spill trajectory purposes, this current has two facets. When wind drag causes a current at the surface of the ocean (wind drift), the wind drift in turn causes currents below the surface of the ocean. The depth to which the "wind driven" currents go depends on the strength and duration of the wind, and of course can be limited by shallow ocean depth. This current which extends from the ocean's surface current might also be called the current in the boundary layer although factors other than wind may determine the depth and nature of the boundary layer. The boundary layer currents set to the right of the wind drift current up to 100° (Stommel, 1954)

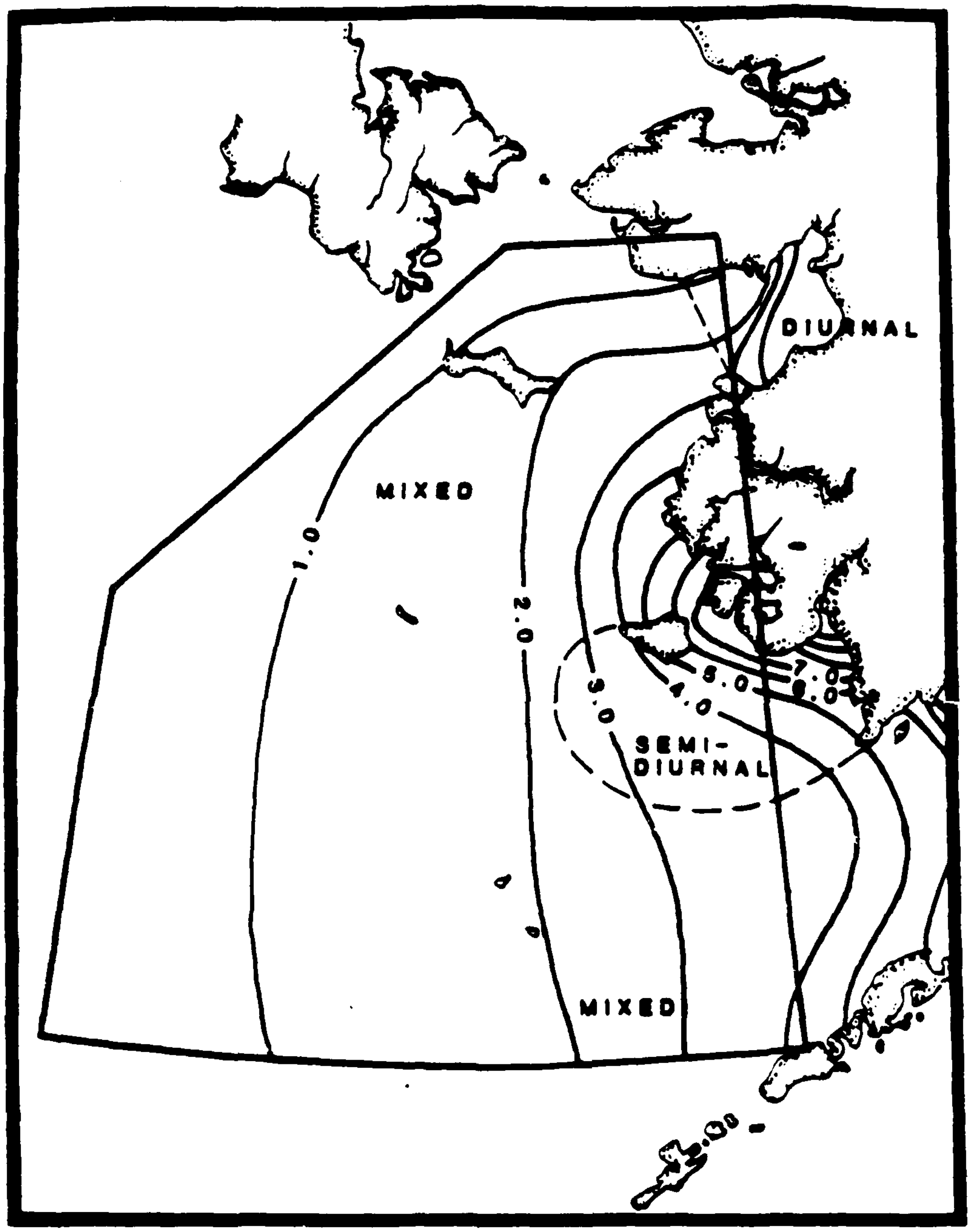


Figure 5.2.2-2. Cotidal lines of Greenwich high water intervals (in hours) and areas of semi-diurnal, diurnal, and mixed daily tidal occurrences. (Pawlowski, R., 1987)

Figures 5.2.2-3. Estimated corange lines (in feet). (Pawlowski, R., 1987)

depending upon speed and duration of the wind as well as other variables. The most likely average angles of transport are shown in Tables 5.2.3-1.

Table 5.2.3-1. Angle (degrees) between the direction of the boundary layer current and the surface wind direction (from Rossby and Montgomery, 1935).

Latitude°	Surface Wind Speed (M/S)			
	5	10	15	20
45	40.6	45.4	48.4	50.9
60	42.0	46.8	50.2	52.7
75	42.6	47.7	51.1	53.8

The direction of the boundary layer currents becomes significant when the pollutant is vertically distributed.

The other facet of wind driven currents (wind drift) is of most importance to oil spill trajectory modeling and forecasting. Wind drift speeds are 2 to 5 percent of the wind speed and the directional deviation ranges generally from 15 to 30 degrees to the right of the surface wind or roughly along the isolines of pressure (isobars) on a pressure analyzed weather map. However, NOAA has done considerable research in recent years in the Bering Sea and NOAA scientists feel that 30 degrees is the best estimate (Pease, C. H., 1987 pers. comm.). Wind drift is the most important factor in oil spill trajectory modeling and forecasting. When vertical distribution of the pollutant is occurring other factors become significant, such as boundary layer currents and tidal currents. For additional discussion of wind driven currents, see Section 6.1.

5.3 Sea Conditions (Waves)

For the purpose and scope of this atlas, sea conditions, seas, sea state, and state of the sea are considered the same. For operational purposes, sea conditions are the roughness of the sea's surface due to wind stress forces - directly or indirectly. There are a variety of other waves in the ocean such as solar waves, lunar waves (tides), tsunamis, gravity waves, capillary waves and others. Wind waves are in the visible spectra (not too long or too short) and are of most importance in normal operations of ships and equipment at sea. They can be seen and described in a variety of ways. Even if they cannot be seen, they can be accurately described from known wind-wave relationships.

Before going into wind-wave relationships, it is necessary to state that the following discussion will be limited to the concept of "combined seas". In open water it is normal that recently developed wind wave sets (seas) are superimposed on swells. Swells are a decaying form of wind wa, sets that have occurred some time ago, or in a distant area, both. Combined seas are these superimposed wave sets. It is possible to have more than one wave set superimposed upon another. For instance wind waves (both seas and swells) may be refracted from steep shore lines, jetties, or even large ships creating a third set of waves all of which contribute to sea conditions.

The National Weather Service (NWS) in their forecast offices has used a simplistic but valuable quantitative definition of the height of combined seas (Cooley, 1977) namely the averaged height of the highest one-third of all wind waves. The algebraic relationship is:

$$H_C = \sqrt{H^2_{SWL} = H^2_{SEA}} \qquad (1)$$

H_C = Height of Combined Seas
H_{SWL} = Height of Swells
H_{SEA} = Height of Superimposed Wind Waves (SEA)

Ex: If Swells are 2 m (6.6 ft)
And Seas are 0.7 m (2.3 ft)
Combined Seas are 2.12 m (7.0 ft)

The above relationship is useful if swells of a known height are moving into a bay, such as Kuskokwim Bay. The swells may be approaching from the southwest while locally generated wind waves may come from the northeast. These are meso-scale situations wherein the combined seas may be significantly different than for broad water areas. The above relationship and example is provided mainly for the purpose of giving the reader an improved concept of the term "combined seas". Also it is important to remember that the roughness, or shape, of the ocean's surface (visible waves) is a function of many things such as fetch, wind speeds (past, present, and distance), wind directions, air mass stability, and others.

Sea conditions have been observed by mariners for centuries, however, it was not until the 20th century that data was compiled in a systematic and retrievable fashion. Using observed data a number of creditable mathematical wind-wave relationships were developed which made it possible to predict combined seas, as well as other ocean characteristics, using wind speed and fetch distance (U.S. Army Corps of Engineers [COE] 1973 and 1984; Pierson, et. al., 1955). Fetch is loosely defined as an area over which the wind is reasonably constant in speed and direction (COE, 1973). The definition of fetch is refined considerably in the U.S. Army COE 1984 Shore Protection Manual (COE 1984), but the following definition by Wise, et. al. (1981) is preferred:

Fetch. An area in which wind direction and speed are reasonably constant and do not vary beyond the following limits:

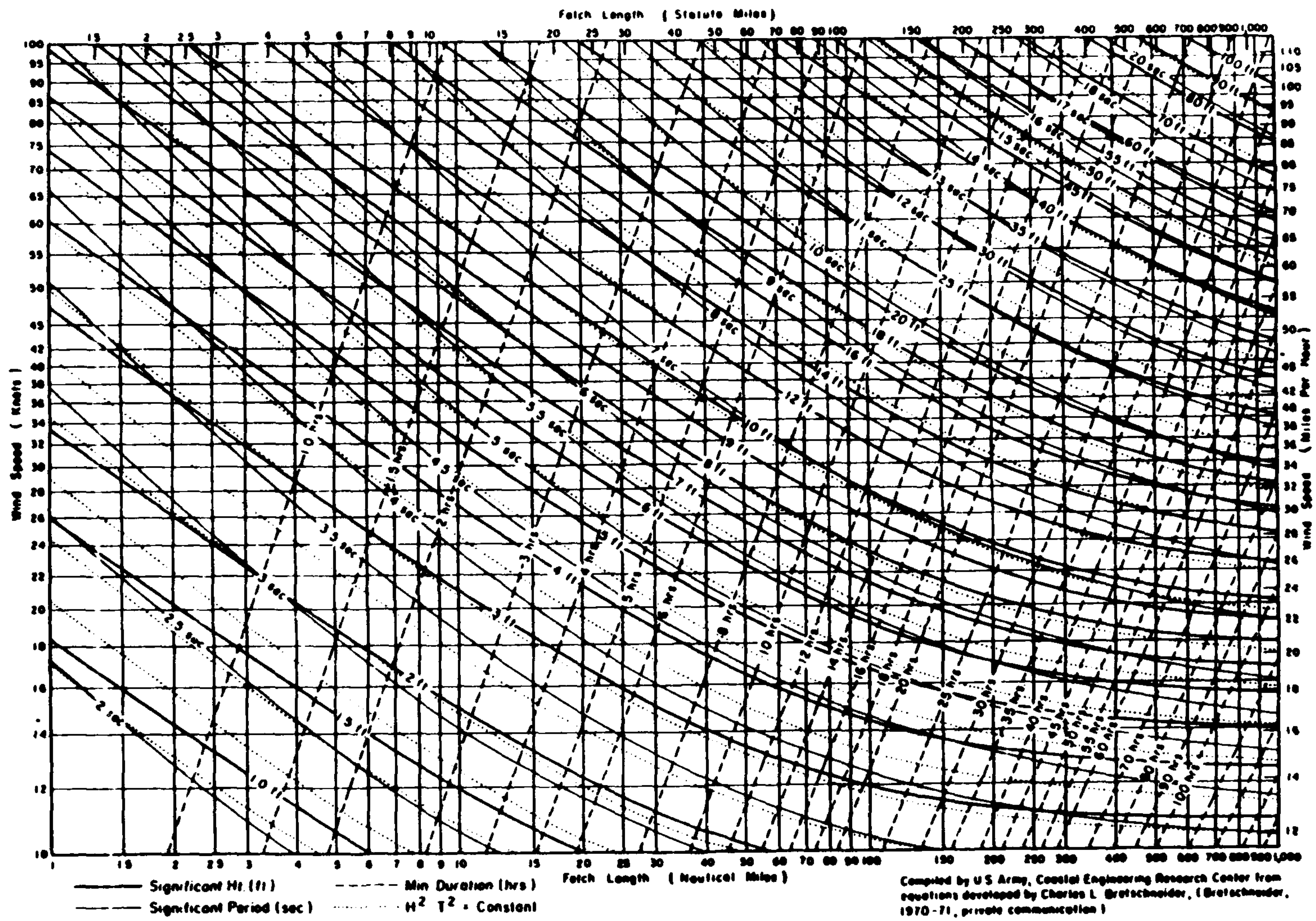
The wind direction or orientation of the isobars does not change direction at a rate greater than 15° per 180 NMI and the total change does not exceed 30°.

The wind speed does not vary more than 20 percent from the average wind speed in the area of direction-fetch being considered. Example: Average wind is 40; acceptable range is 32 to 48.

A number of wind-wave numerical relationships were developed in the late 1950's and the entire 1960's (COE, 1973 and 1984). Using a Bretschneider (1970-71) version of the many wind-wave equations, the COE developed a nomogram (Figure 5.3-1) wherein wind speed and fetch length can be used to derive combined seas as well as period of the significant seas. Period is defined as the interval of time between significant wave crests. The curves on the COE nomogram (Figure 5.3-1) will be referred to as the Bretschneider Nomogram.

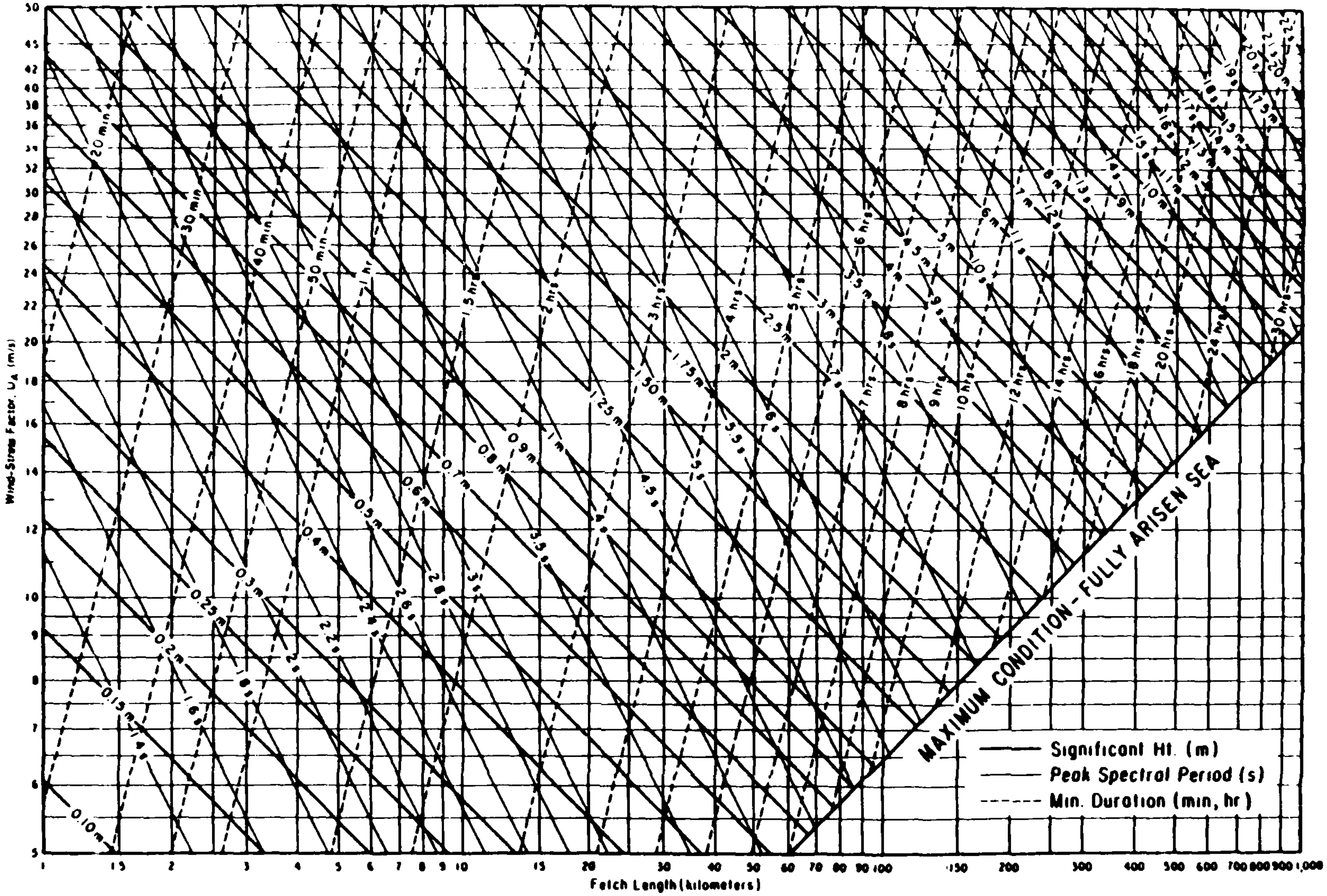
Beginning in 1967 the Joint North Sea Wave Project (JONSWAP) which generated oceanographic wave data from sensors placed on buoys, masts, and from aircraft overflights (DOC NOAA, 1981). From these data, another set of equations were developed by Hasselman, et al. (1973). From the Hasselman equations, the COE developed another nomogram to derive combined seas from wind speed and fetch length (COE, 1984). Figure 5.3-2 and 5.3-3.

The Bretschneider Nomogram has been widely used with reasonable success but it is entirely possible that the Hasselman Nomogram is superior, particularly in the Bering Sea, because of the different character of the JONSWAP data (buoys, etc. as opposed to shipboard observations) as well as the geographic location



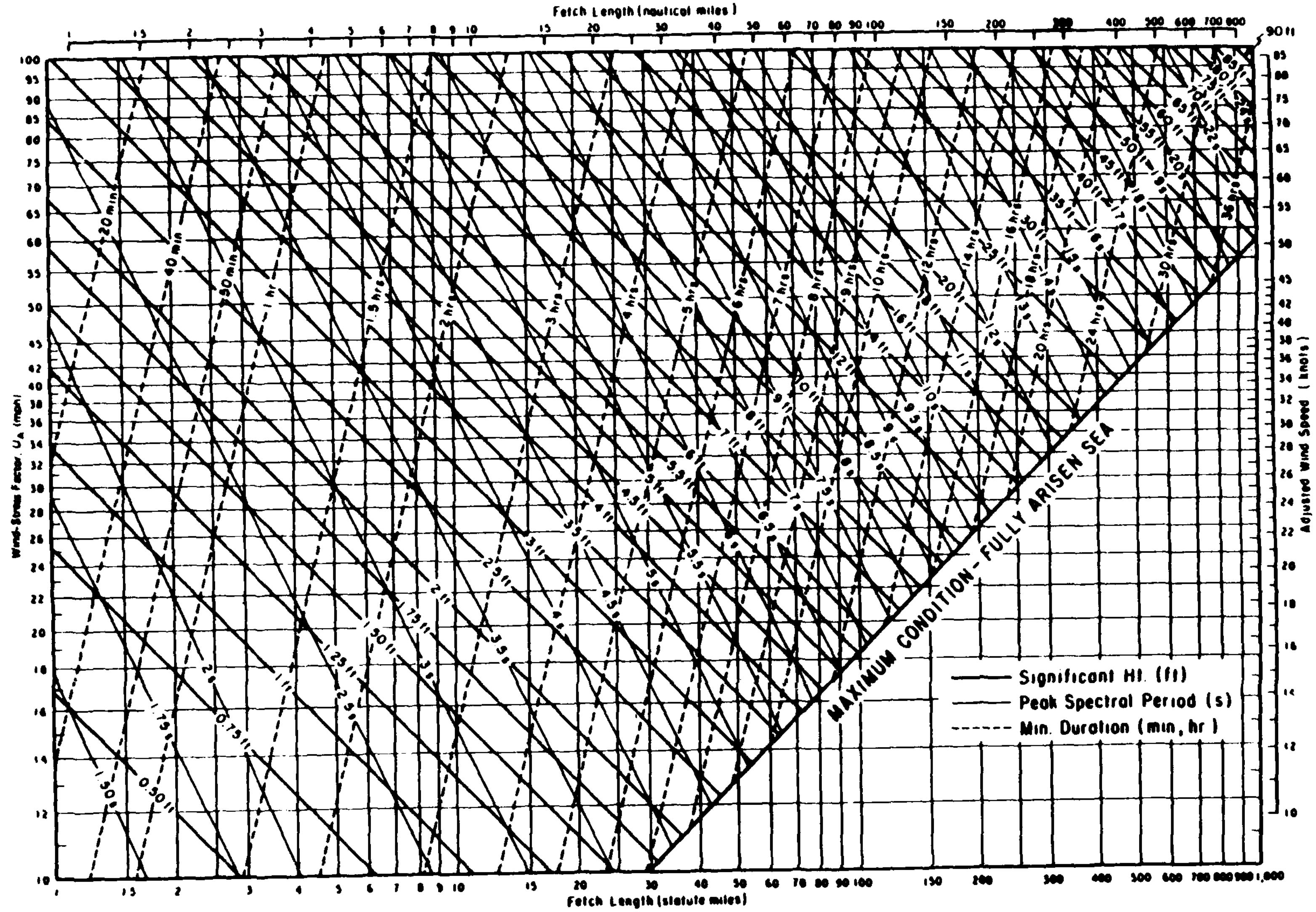
BRETSCHNEIDER NOMOGRAM

Figure 5.3-1. Deepwater wave forecasting curves as a function of wind speed, fetch length, and wind duration (for fetches 1 to 1,000 miles).



HASSELMAN NOMOGRAM (Metric Units).

Figure 5.3-2. Nomograms of deepwater significant wave prediction curves as functions of windspeed, fetch length, and wind direction.



HASSELMAN NOMOGRAM (English units).

Figure 5.3-3. Nomograms of deepwater significant wave prediction curves as functions of windspeed, fetch length, and wind duration.

from which the data was compiled - in the North Sea at approximately 55° N and 7° to 8° E (Hubert, 1987). Both nomograms are presented and can be tested aboard ship using observed winds, or using forecast winds if the ship is capable of receiving weather maps via facsimile or other similar recording device.

A series of nomograms was also developed for shallow water of uniform depth (Figures 5.3-4 through 5.3-13). These nomograms are particularly useful in estimating wave heights nearshore. For shipboard operators and on-scene coordinators the nomograms can be extremely valuable in refining marine forecasts of sea conditions as issued by the National Weather Service (NWS). It is important to remember that the NWS normally issues only "area" forecasts as opposed to site specific or "spot" forecasts. Frequently the seas within an area will be much more variable than the winds within the same area. Thus the NWS forecast winds can be used for spot forecast sea conditions using the nomograms described above and presented in Figure 5.3-1 through 5.3-13. If wind observations are used, as opposed to wind forecasts, the wind speed can be used directly with little error if the measurement height is between 10 and 30 m. If higher or lower, the wind speed should be corrected to 20 m using the equation described in 6.1.

For oil spill trajectory modelers, it is important to determine which nomograms best describe the seas and to consider all significant parameters. It is particularly important to lower or raise the wind speed to the model level if the model is calibrated to NWS wind levels. It is important to consider how the model might perform in a given "spot".

NWS forecast users should know that the NWS coastal forecasts in Alaska normally extend from the coast outward 60 nmi. With an offshore wind the maximum seas will be located well offshore. These are the seas that are forecast for that entire marine forecast area. If the maximum wind occurs in one corner of the

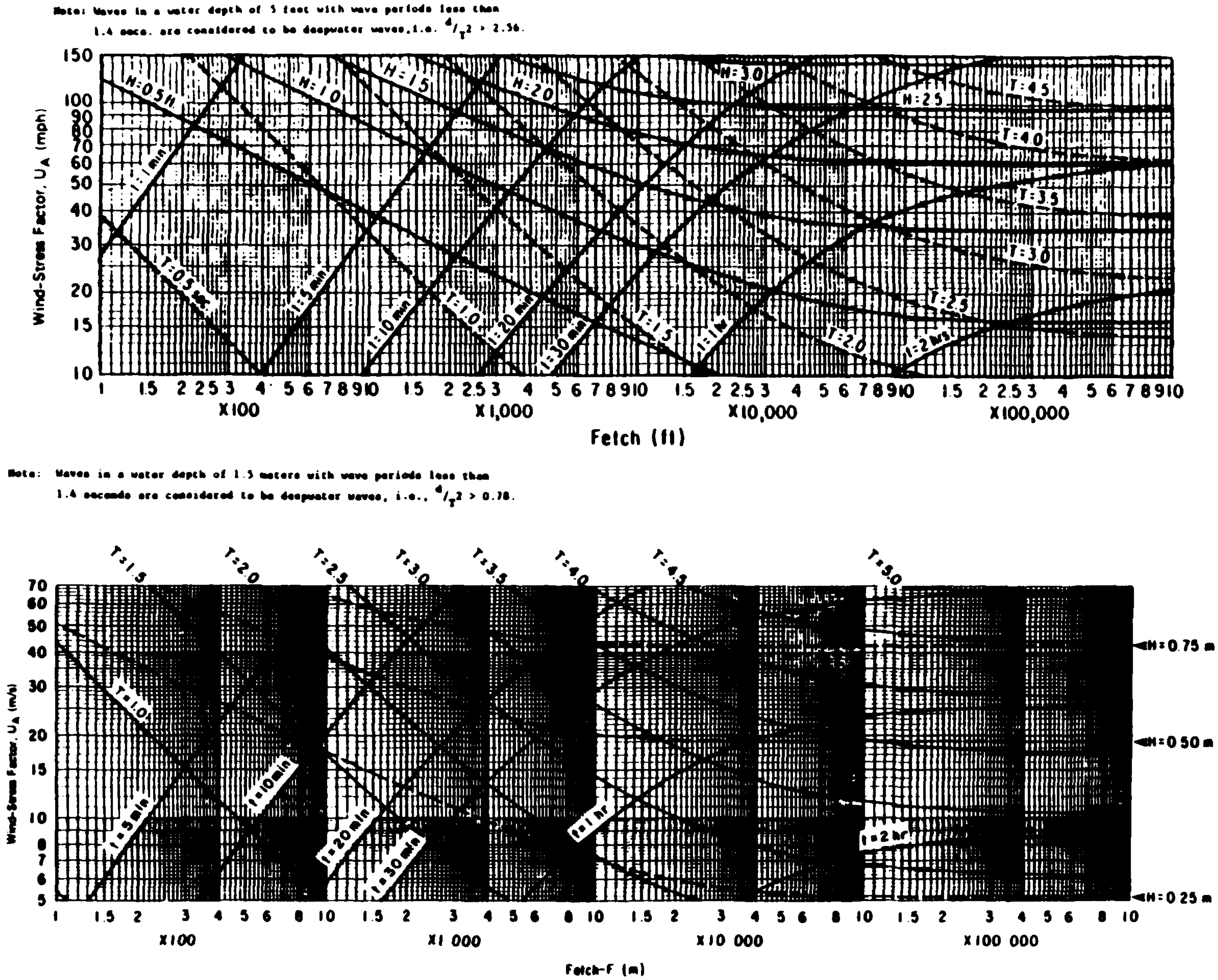


Figure 5.3-4. Forecasting curves for shallow-water waves; constant depths = 5 feet (upper graph) and 1.5 meters (lower graph).

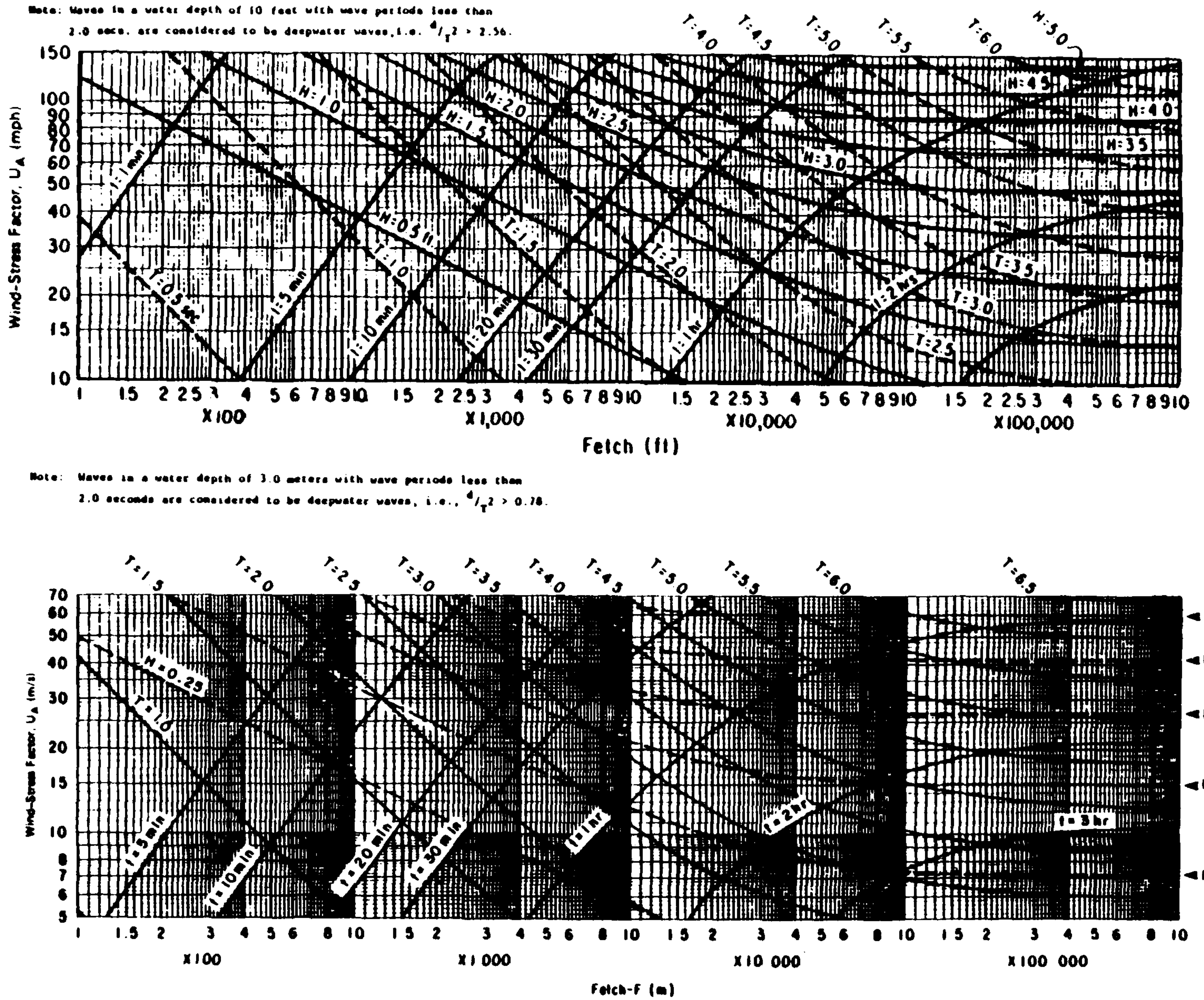


Figure 5.3-5. Forecasting curves for shallow-water waves; constant depths = 10 feet (upper graph) and 3.0 meters (lower graph).

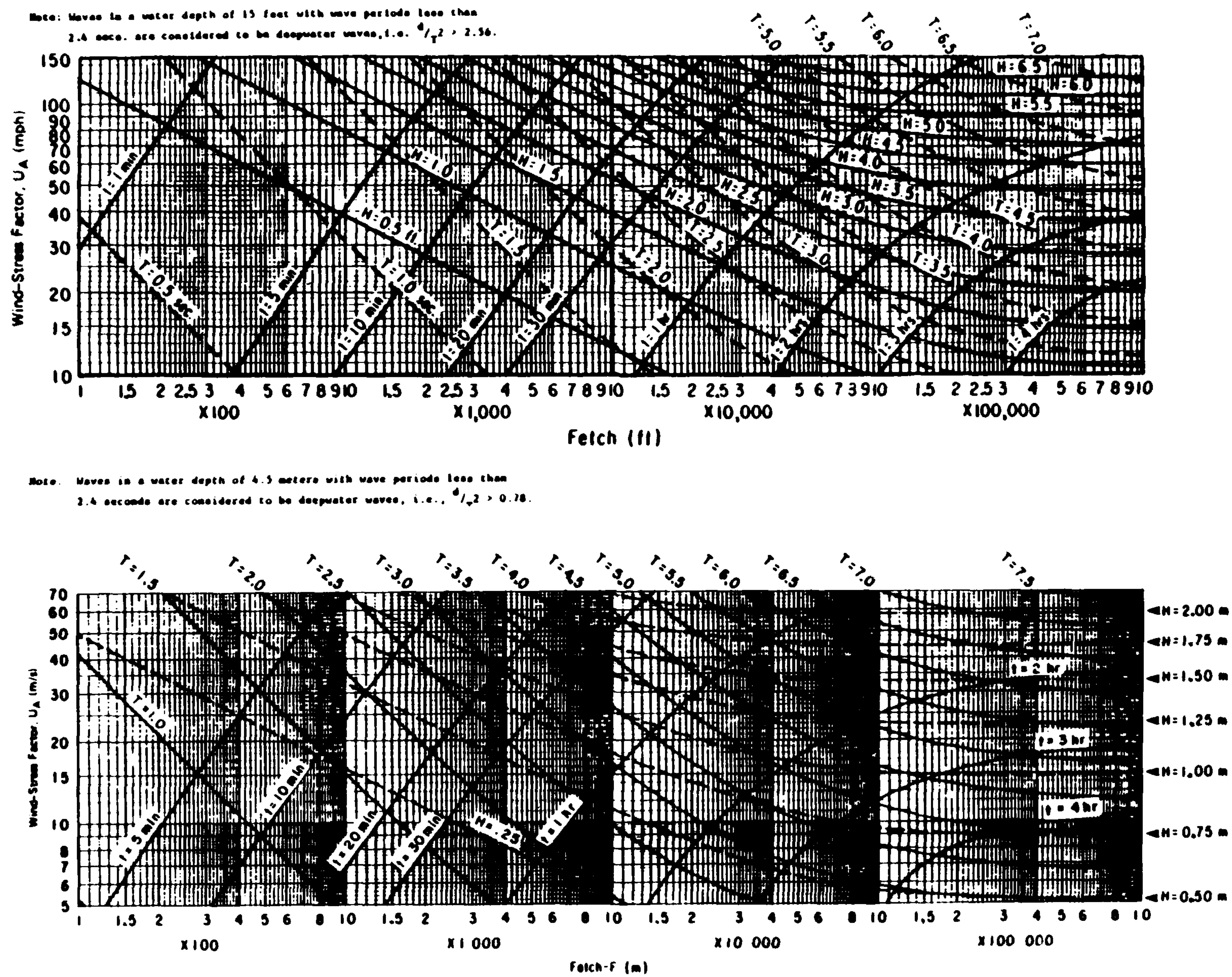


Figure 5.3-6. Forecasting curves for shallow-water waves; constant depths = 15 feet (upper graph) and 4.5 meters (lower graph).

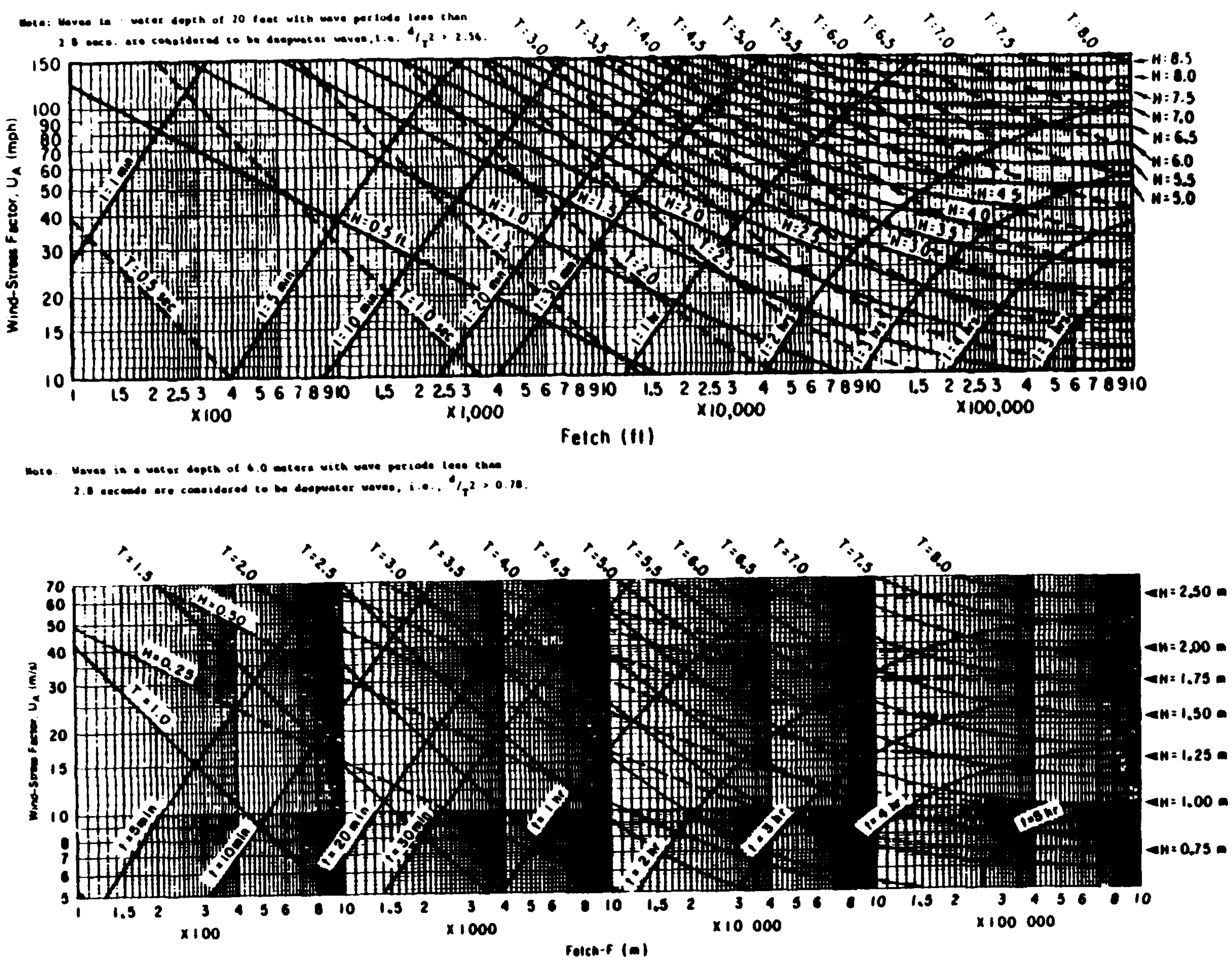


Figure 5.3-7. Forecasting curves for shallow-water waves; constant depths = 20 feet (upper graph) and 6.0 meters (lower graph).

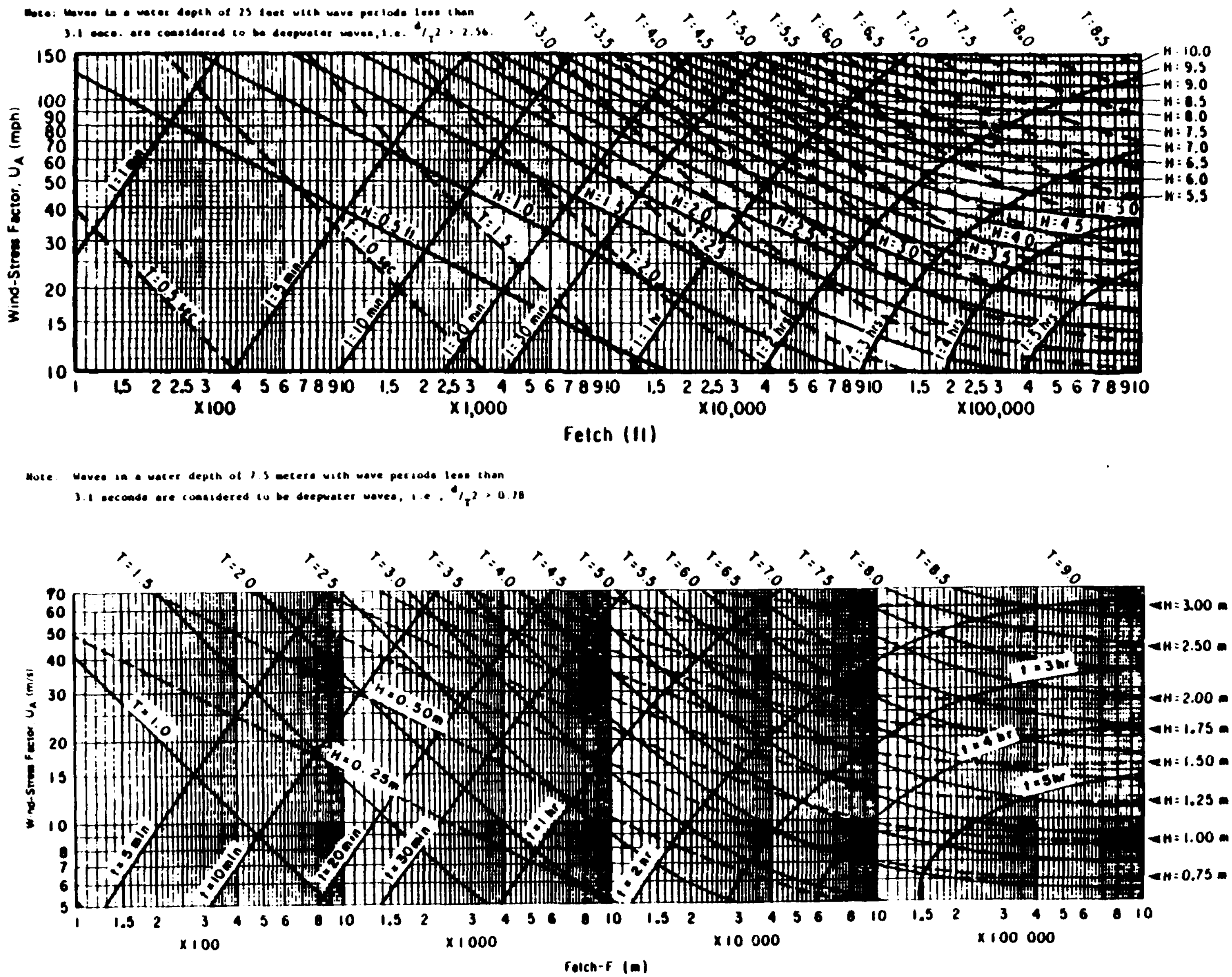


Figure 5.3-8. Forecasting curves for shallow-water waves; constant depths = 25 feet (upper graph) and 7.5 meters (lower graph).

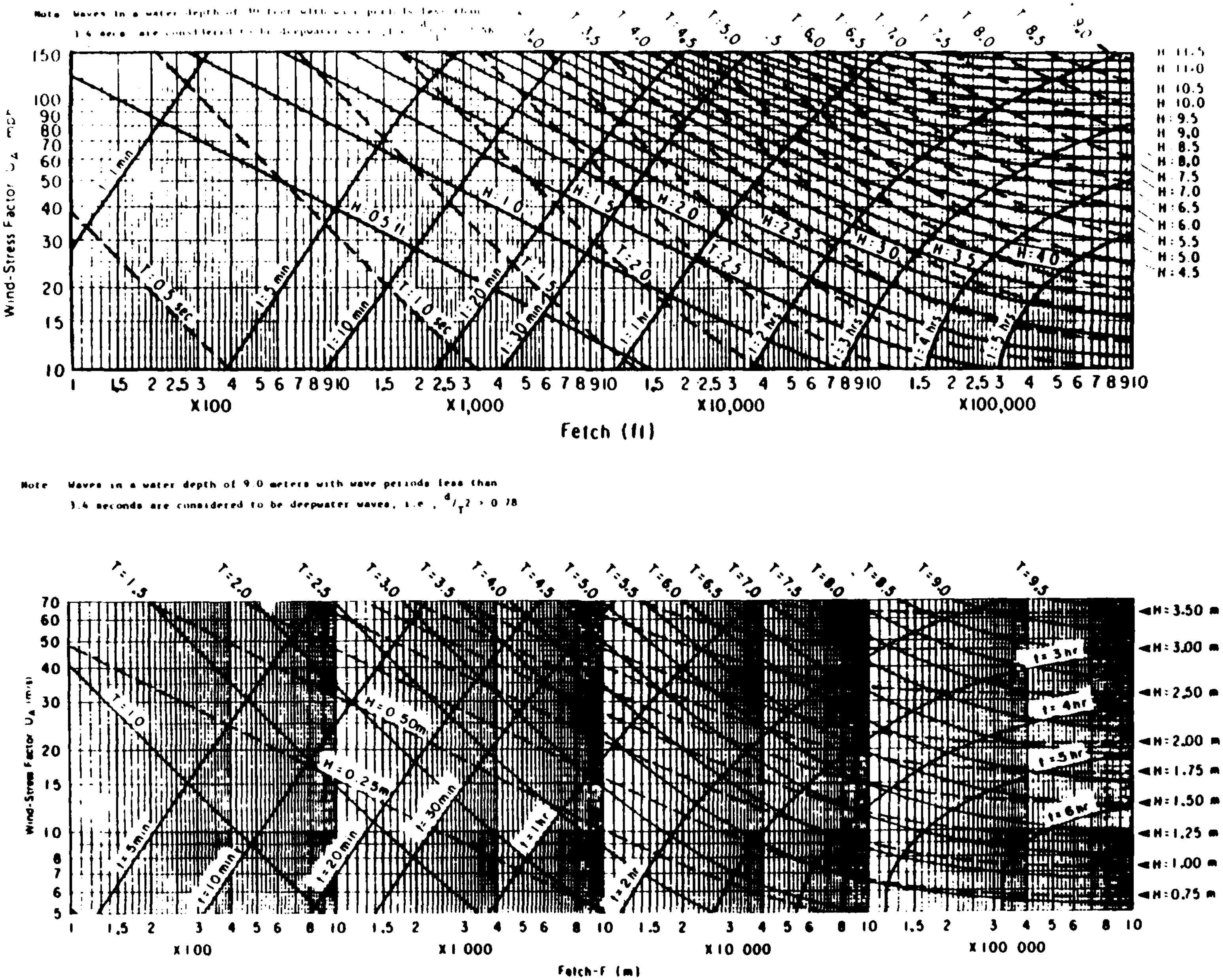


Figure 5.3-9. Forecasting curves for shallow-water waves; constant depths = 30 feet (upper graph) and 9.0 meters (lower graph).

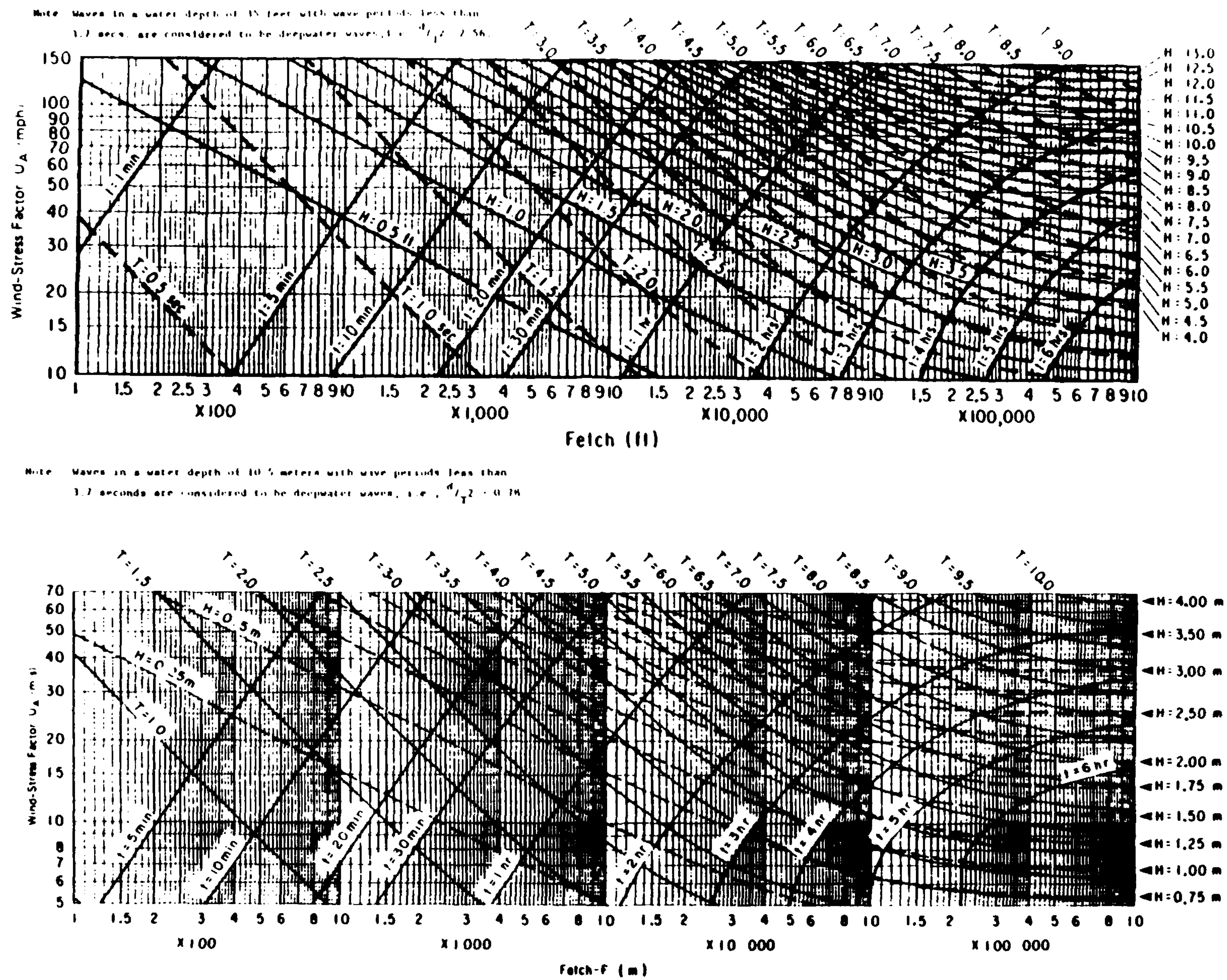


Figure 5.3-10. Forecasting curves for shallow-water waves; constant depths = 35 feet (upper graph) and 10.5 meters (lower graph).

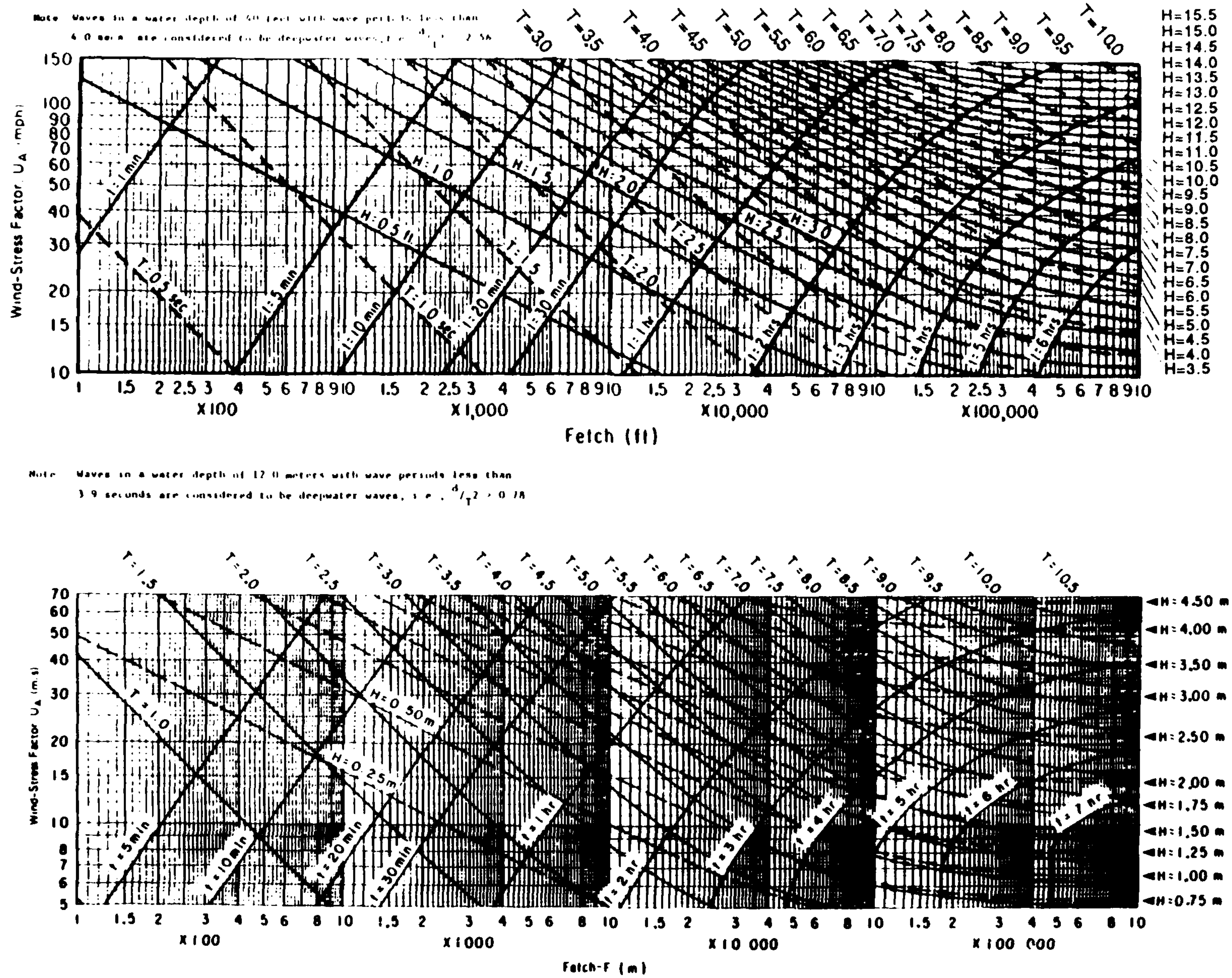


Figure 5.3-11. Forecasting curves for shallow-water waves; constant depths = 40 feet (upper graph) and 12.0 meters (lower graph).

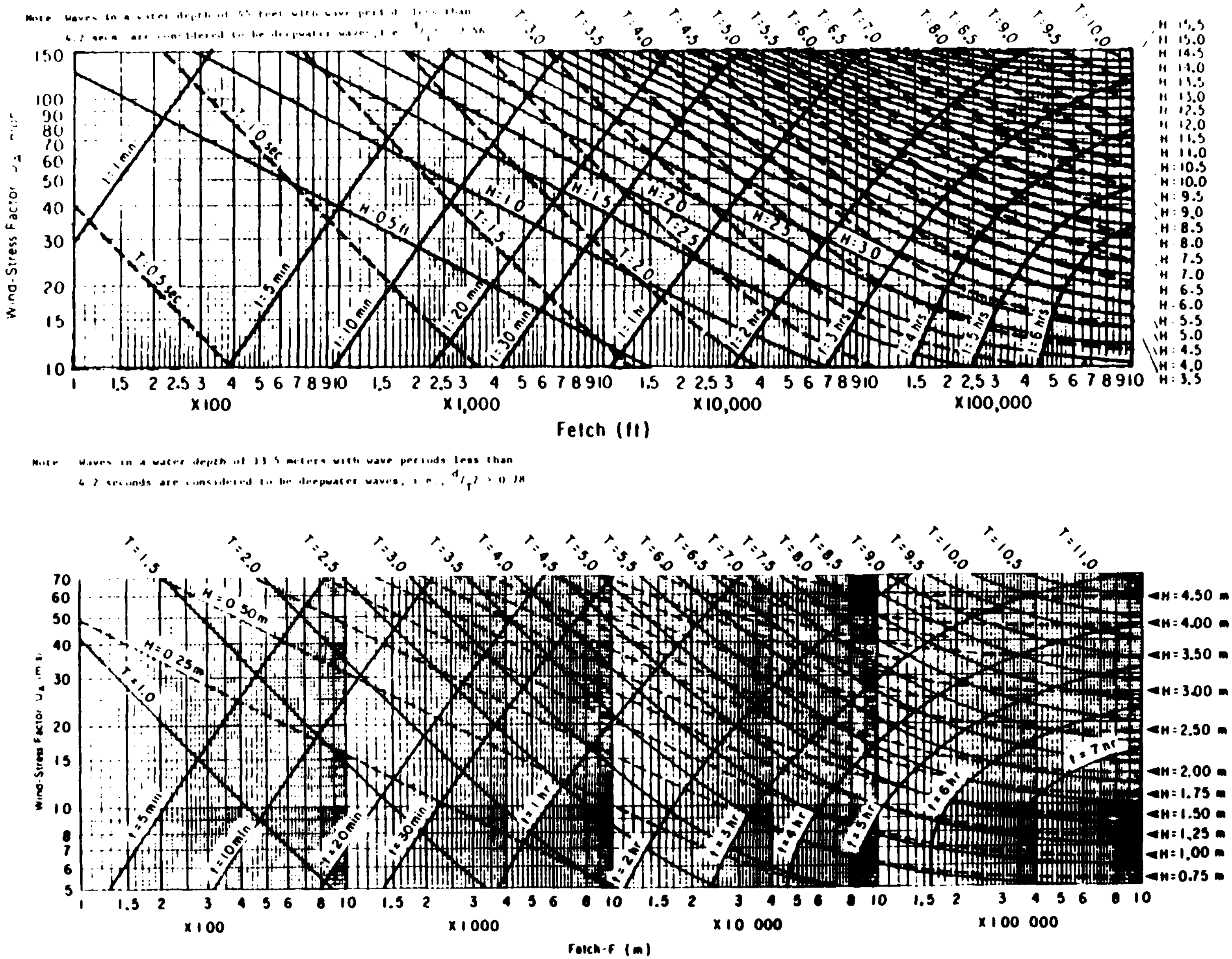


Figure 5.3-12. Forecasting curves for shallow-water waves; constant depths = 45 feet (upper graph) and 13.5 meters (lower graph).

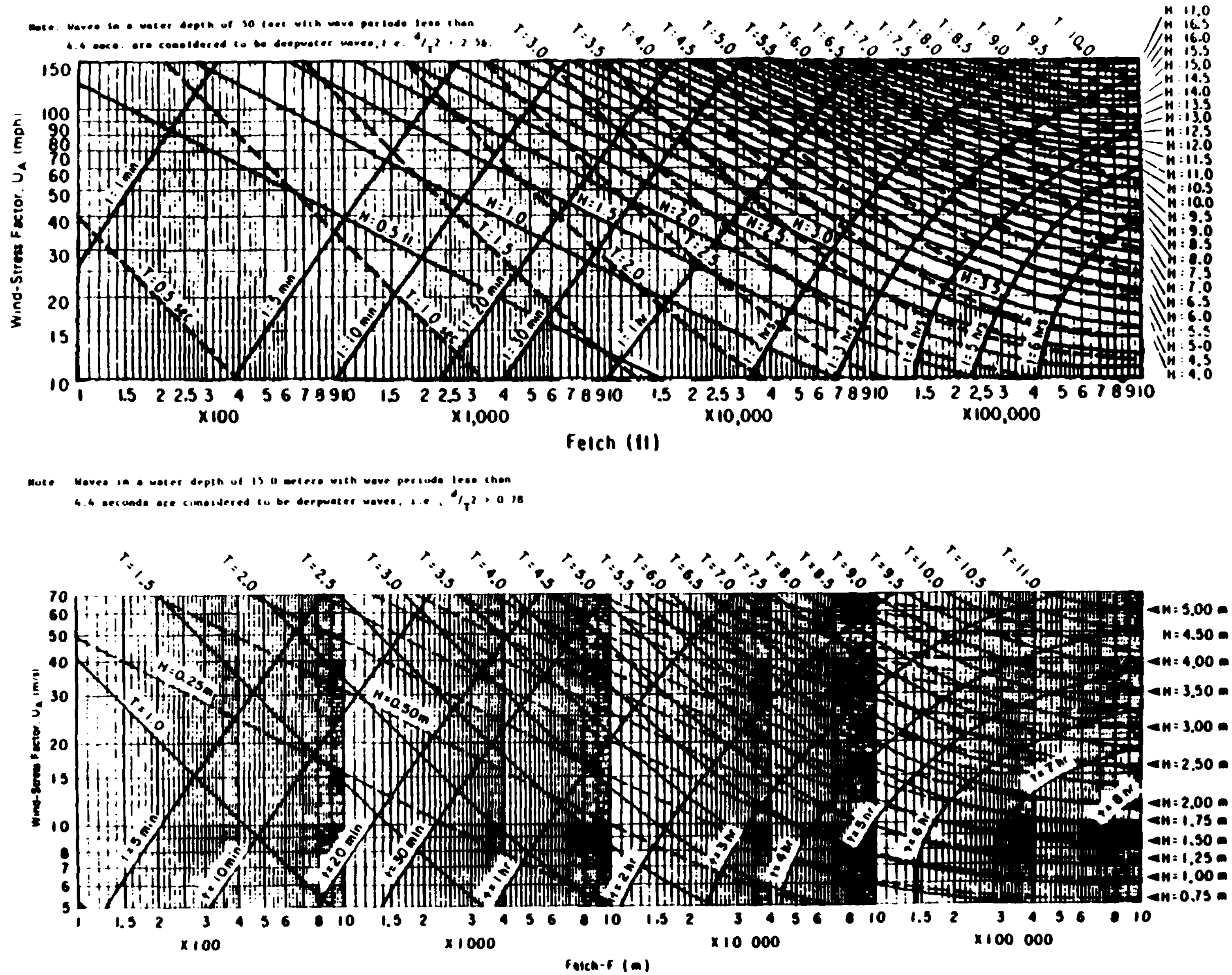


Figure 5.3-13. Forecasting curves for shallow-water waves; constant depths = 50 feet (upper graph) and 15.0 meters (lower graph).

forecast area, these are the winds that will be forecast. The result is that sea conditions may be overforecast. In the other direction, the NWS forecasts do not take into account the affects of tidal currents, schoaling and topography, all of which can affect sea conditions, either up or down, thus it is important to look at the NWS forecast closely and make adjustments if necessary.

Figure 5.3-14 shows the NWS marine forecast areas for western Alaska and the Bering Sea. The forecast area outlines were obtained from DOC NOAA Marine Weather Services Chart (MSC-15-ALASKAN WATERS). MSC-15 contains information on all NWS marine forecast areas, marine broadcast frequencies and sources from both commercial and government sources. Also included is the U.S. Coast Guard Weather Radiofacsimile Transmission Schedule and other information. It is recommended that all vessels operating in Alaska waters have a copy of MSC-15 which is usually updated yearly by the NWS.

5.4 Sea Surface Temperatures, Salinity and Suspended Sediments

Sea Surface Temperatures (SST) are not well documented in the Bering Sea, however, Brower, et.al. (1977), and the NOAA-NWS Oceanographic Monthly Summaries indicate that mean August (warmest SST month) temperatures range from 11°C (52°F) along the Aleutians to 5°C (41°F) near 65°N. Yearly variations do not usually exceed 2°C. In March (coldest month), temperature range from 3°C (37.4°F) near the Aleutians to approximately -1.8°C (28.8°F) at the ice edge beyond which it remains almost constant. The southern SST's can vary by 2°C with less variability as the ice edge is approached.

The SST is important in predicting the rate of superstucture icing. It is also a factor for predicting rate of oil spread in some prediction models. Water temperature, volume of oil, and oil type dominate the rate of spreading (Fay, 1969).

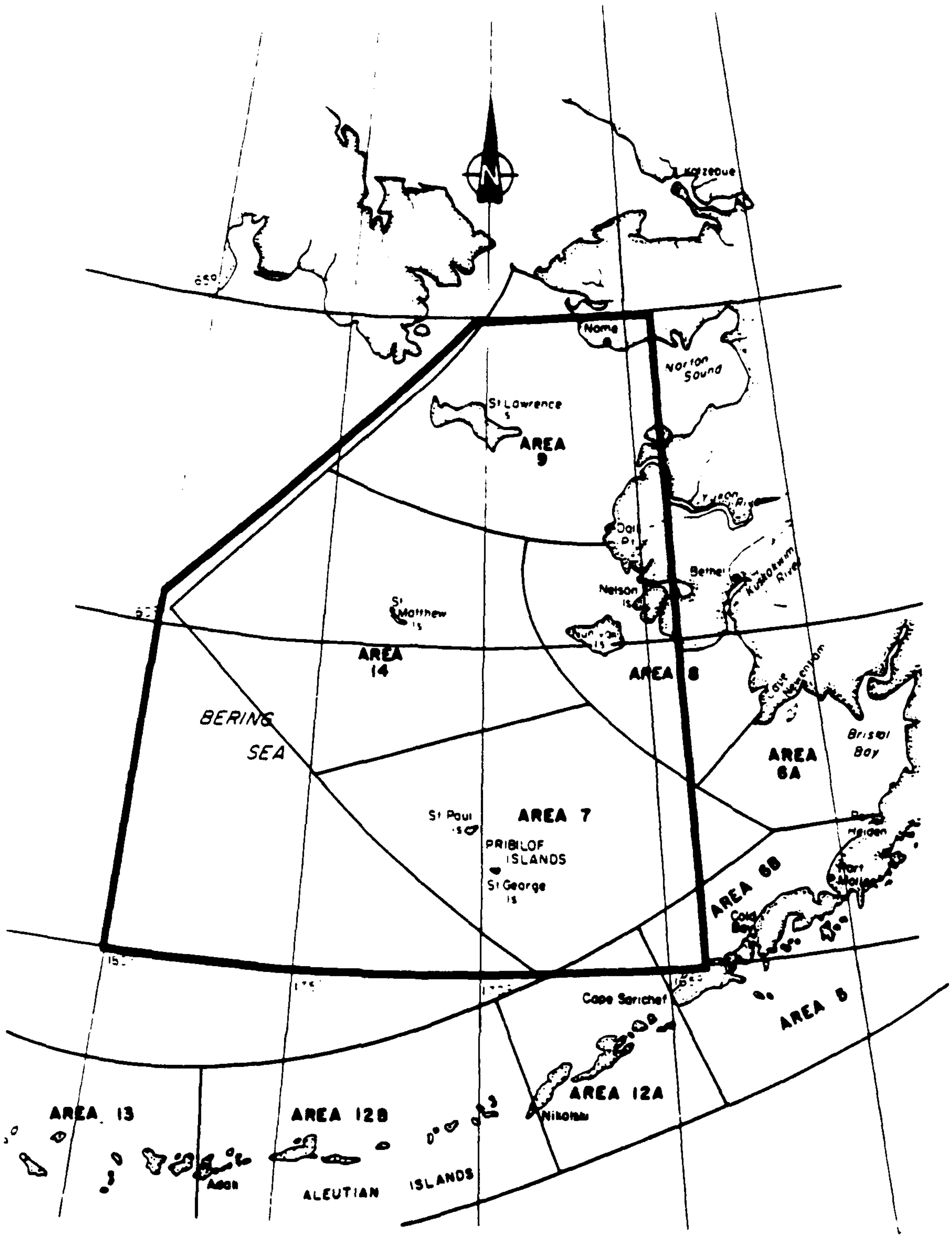


Figure 5.3-14. National Weather Service (NWS) marine forecast areas and Bering Sea Atlas area is depicted. Attention to Aleutian Chain forecast areas (5, 12A, 12B, 13) is frequently useful for advance warning of weather entering areas 7, 8, 9, and 14.

Salinity ranges from approximately 31.3 parts per thousand (ppt) to 33 ppt (Schumacher, 1982) with lesser values along the mainland coast and especially near the Yukon and Kuskokwim River mouths.

5.5 Storm Surges

Oceanographically, a storm surge is one of several long waves which occur in the ocean. Other long waves are tidal waves generated by the moon and the sun, and tsunamis (something erroneously called tidal waves) generated by under water earth movements. Storm surges are usually identified by anomalous readings on a tide gauge, or flooding along the coast. Because there are no permanent tide gauges north of the Aleutians, most storm surges in the Bering Sea are manifest by flooding of low lying coastal areas.

For storm surges to occur there must be special atmospheric and bathymetric conditions. Strong winds must blow over a significant period of time and from specific sets of directions. Low atmospheric pressures are also a factor. In addition, the offshore ocean area should be broad and shallow as in the Bering Sea. The bathymetric conditions are static and amiable to storm surges, thus whenever the atmospheric conditions are right, storm surges occur. Once again, the surges are manifest by coastal flooding, however, surges can go completely unnoticed if they occur near a precipitous shoreline or headland such as Cape Romanzoff or Cape Vancouver simply because there is little low lying land and consequently little flooding. In areas with precipitous shorelines, surges are positively identified only with tide gauges.

Studies by Pease, et al. (1982) indicate that numerous storms enter the Bering Sea. Their movement is mostly from southwest to northeast with more frequent storms in the southern half of the Bering Sea than in the northern half. Thus it is logical to conclude that storm surges are relatively common. However, when one considers the scarcity of people along the coast and the lack of tide gauges, it is likely that only a very small percentage of even significant surges are noticed or recorded. A significant surge might be defined as any surge over 1.5 to 2 m depending on minor variations in the height of coastal land. Finally, no significant surge is likely if the Bering Sea ice pack extends more than 50 nmi from shore.

The storm surges of the Bering Sea are similar to surges caused by hurricanes along the east and Gulf coast of the United States. For further information and discussion, see Section 6.7, and Appendix B.

5.6 Superstructure Icing

Superstructure icing is the freezing of liquid water on marine structures. Marine structures are defined as ships, boats, skimmers, booms, or anything on or near the ocean that may be subject to freezing spray. Superstructure icing is most frequently caused by waves hitting the structure and causing spray with the spray subsequently freezing on the structure. Freezing spray has accounted for all the ships lost in icing incidents in Alaska.

In early winter as insolation decreases and cold winds from Alaska or Siberia flow over the Bering Sea, the sea surface temperature drops to near freezing. In December as very cold air begins to flow over the cold water, superstructure icing begins anytime the wind is strong enough to create waves which in turn creates spray. However, if the cold winds are persistent, sea ice forms over the water. The sea ice inhibits wave development and associated spray. Thus nature tends to obviate superstructure icing in the northern Bering Sea because of the persistent ice cover there. The southern Bering Sea has open water most of the time, thus cold winds from the north or northeast create waves and freezing spray.

In the central Bering there may be ice or open water, but if open water exists the risk of freezing spray is not as great as in the southern Bering. This is because the ice usually located in the northern Bering has the same affect as a land mass in limiting the fetch of wind over water and consequently limiting wave height and freezing spray. The necessary factors of strong winds, cold air and cold sea temperatures occur from December until the last half of March at which time the land masses begin receiving considerable solar radiation and the continental air warms considerably. Consequently, even though the sea water temperature remains cold (in April), freezing spray does not occur or it occurs with much less severity than in mid winter. A method for forecasting superstructure icing rates and additional information is contained in Section 6.4.

5.7 Sea Ice

Sea ice is a major oceanic atmospheric phenomena in the Bering Sea. Ice formation begins in October and the ice pack extends into the southern and southeastern Bering Sea by late January and March (Potocsky, 1975) and frequently persists until April after which it retreats rapidly to the north or disintegrates in a disorganized way. The ice varies in thickness with the thickest ice and the largest flows most likely to be found between the Yukon Delta and St. Lawrence Island thence northward towards the Seward Peninsula and the Bering Strait. During the time of maximum ice cover, the thickest ice is in the area indicated above with thinner ice in eastern Norton Sound, the central Bering Sea and along the southern coasts of St. Lawrence Island, St. Matthews Island, and Nunivak Island.

The ice is subjected to a variety of forces which determine the extent and character of the ice. The primary forces are wind, tide and temperature. Because wind and temperature are prime factors in ice formation, and because these factors fluctuate from year to year, there is considerable fluctuation in ice coverage and character.

Sea water temperatures and tides are much more conservative than the weather (their seasonal changes are small) and these oceanic parameters can be considered constant for day-to-day computational purposes. A change of 1 degree celsius in the water column over several days is considered large; however, changes of 3 to 5 degrees in the extreme upper layers can occur in a short period of time (24 hours) with a sudden outbreak of very cold air over relatively warm water. For instance, a large and intense storm moving into the Gulf of Alaska can cause outbreaks of cold continental air (temperatures -18 to -10°C) for several days over the Bering Sea. Figure 7.1-2 depicts such a situation. See Chapter 7.0 for a full discussion of sea ice.

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6.0 CLIMATOLOGY AND METEOROLOGY

6.1 Wind and Wind Driven Currents

The wind driven currents are most important when considering oil spill transport. Thus it is important to look closely at the relationship of winds to wind driven currents. Sustained winds can cause "wind driven currents" in the ocean to a considerable and variable depth depending on the duration and strength of the wind and other variables such as latitude, density (water and air), oceanic baroclinicity, etc. In this discussion, and in the atlas in general, the term "wind driven current" refers to only the topmost layer of the ocean - the layer in which the bulk of the oil is initially transported. The winds can be classified into two general groups: (1) climatological, and (2) real time (episode) winds.

6.1.1 Climatological Winds and Currents

Climatological winds can be considered for various periods of time ranging from monthly, seasonal, and longer periods of time. The monthly summaries of the coastal and island stations reveal that in the northern Bering Sea the prevailing wind directions are from the northeast tending to become bimodal (NE and SSW) in May. In July and August, the winds are still bimodal, but the prevailing direction is southwesterly. Beginning in September, the prevailing direction is north-northeast until January, then becoming mostly northeasterly from January to May. The lightest winds are in June and July. The strongest are from October to March when winds in excess of 25 m/s (48 kts) have been reported.

In the southern Bering Sea, the climatological winds tend to be more northerly (northwest to northeast) during all months except July and August when they are from the south to west. June tends to be bimodal - north or south. The strongest winds occur from October to March, and the maximum winds reported are slightly more frequent than in the northern Bering Sea.

The wind data in Section 6 is considered to be reasonably representative of winds over the water and ice because the stabilizing or destabilizing effects of the ocean are reflected in wind speed and direction and the modifying effects of land are minimal because of the short trajectory over land. Cape Romanzoff is excepted somewhat because it is located on the mainland coast as well as on a promontory. At Cape Romanzoff, mainland atmospheric conditions could make the Romanzoff data non-representative of marine conditions. Northeast Cape is also located on a promontory, but is more representative than Cape Romanzoff because of the greater influence of the Bering Sea.

In addition to the qualifications described above, we must also remember that 1) wind measurements over land are taken at 10 m, on most ships at 19 - 20 m, and on drill rigs at 30 - 90 m; 2) the frictional affects over water are usually less than over land; 3) the stability of air over water varies considerably. The effects of stability are discussed extensively in Section 6.3.

General circulation currents (Figures 2.3-1 and 2.3-2) should tend to be correlated to climatological winds and this appears to be the case. However, the correlation appears to be weak and it is obvious that other atmospheric and oceanic forces affect the general circulation.

6.1.2 Real Time Winds and Currents

Real time surface currents are highly correlated to real time winds. The real time or actual winds during an oil spill episode may differ significantly from the climatological winds, and because the oil spill trajectory models are driven by, or sensitive to, the real-time winds, it is important that the real time wind data input be as accurate as possible.

Most models will perform reasonably well when using accurate wind input; however, there are at this time two significant weaknesses in the wind reporting system. Those weaknesses are: 1) the wind speed is not always reduced to the wind elevation (reference level) to which the model was designed, and 2) either the reduction procedure or the model does not provide for the effects of atmospheric stability on the wind itself. For instance, if the wind speed is measured at 60 m, it may not be representative of the wind at 20 m or any other reference level wind required by the model. In addition, unstable air will exert a greater shearing force on the water surface, and consequently, a greater wind-driven current than stable air. Drill ships tend to measure and report winds at the 30 m level. Drill platforms tend to measure and report winds at the 50 to 100 m level. To further complicate matters, the wind forecasts provided routinely to the drill rigs are anemometer level (30 to 100 m) winds. Thus, if the wind forecasts are correct for the anemometer level, they are not correct for the model.

In addition, when one realizes that wave, ice movement, and superstructure icing models as well as oil spill trajectory models are primarily wind driven, it becomes quite important that winds be reduced to a correct reference level, particularly when strong winds during stable conditions are occurring. Strong winds and stable conditions have the greatest vertical wind shears (change of wind speed with height). Interestingly, when an observer estimates the wind speed from the sea state, the estimated wind closely approximates the measured wind at 20 m (Quayle, 1980).

There are several formulae for reducing a measured or forecast wind to a desired level. The vertical wind speed profile tends to approximate a natural logarithmic curve. The general form of the equation is:

$$\frac{U_H}{U_R} = \left(\frac{H}{R}\right)^k \tag{1}$$

Where U_H = measured wind at H

U_R = reference level wind (usually 10 or 20 m)

H = height of measured wind

R = height of reference level

k = a constant that may vary according to application

One suggest value of k is 0.143 (Elliot, 1979). The equation does not provide for differences in air mass stability but the reference level wind can now be estimated by:

$$U_R = \frac{U_H}{\left(\frac{H}{R}\right)^{.143}} \tag{2}$$

The exponent of 0.143 most likely represents the vertical wind profile over land.

A more refined estimate of the reference level wind (U_R) which takes into consideration air mass stability, as indexed by the air-sea temperature difference to the wind values derived by Smith (1981), can be derived from the following equation developed by NORTEC for the Norton Sound Atlas (NORTEC, 1987).

$$U_R = \frac{U_H - .0028\ (T_a - T_s)\ (H_m - H_r)}{\left(\frac{H_m}{H_r}\right)^{0.11}} \tag{3}$$

U_R = wind at reference level in m/s
U_H = measured wind at height H in m/s
T_a = air temperature in degrees Celsius
T_s = sea temperature in degrees Celsius
H_m = height of measured wind in meters
H_r = height of reference wind in meters

Equation (3) yields approximately the wind values given in Table 6.1.2-1. If we reverse the procedure and assign a wind of 20 m/s at 90 m and then reduce the wind to 10 m, still using equation (3), we find that for $T_a - T_s = -10$ (unstable) the computed wind for 10 m is 17.5 m/s, a reduction of only 2.5 m/s. For $T_a - T_s = 10$ (stable) the computed wind is 14.0 m/s, a reduction of 11.65 kts (from 39 kts to 27.5 kts). When one considers that a five knot change in wind speed can equate to a 1.5 m (5 ft) change in sea height as well as changes in oil spill transport speeds, it is apparent that the wind speeds used for oil spill containment planning must be used with care.

In general, the speed of the wind driven current is 2 to 5 percent of the 10 m wind speed (Wiegel, 1964). Measurements of surface wind driven currents are not easily accomplished. Factors affecting variability of wind-driven currents are the coriolis force, tides, general circulation, surface roughness,

Table 6.1.2-1 The wind values derived from equation (3) are given for a wind speed of 20 m/s at a reference 10 m level over a set of constant air-sea temperature differences.

STABILITY (T_a-T_s)					
Elevation	Very Unstable $T_a-T_s=-10$	Stable $T_a-T_s=-5$	Neutral $T_a-T_s=0$	Stable $T_a-T_s=+5$	Stable $T_a=T_s=+10$
10m	20 m/s	20 m/s	20 m/s	20 m/s	20 m/s
20m	21.3	21.5	21.6	21.8	21.9
30m	22.0	22.3	22.6	22.9	23.1
40m	22.5	22.9	23.3	23.7	24.1
50m	22.8	23.4	23.9	24.0	25.0
60m	23.0	23.7	24.4	25.1	25.8
70m	23.1	23.9	24.8	25.7	26.5
80m	23.2	24.3	25.1	26.1	27.1
90m	23.2	24.5	25.5	26.6	27.7

air mass stability and even the design of measuring equipment (Wiegel, 1964). However, from the collective measurements and theoretical derivations described by Wiegel, when considered in concert with wind induced ice movements (Overland, 1985a; Pease et al. 1983; Macklin 1983), it is reasonable to assume that the speed of wind-driven currents are largely a function of wind speed, ocean roughness and stability of the atmosphere. In general terms then, light winds, smooth water surfaces and stable air (air warmer than water) equate to a wind-driven current of 2 percent of the wind speed. Conversely, at the other extreme, high winds, a very rough surface and very unstable air (air colder than water) equate to a wind-driven current of 5 percent. We recognize that high winds, roughness, and stability are interrelated but not necessarily so. For instance, it is possible to have high winds with relative water smoothness when the fetch is short. It is also possible to have roughness without instability, etc. Keep in mind that wind measurements should be reduced to the desired reference level, usually 10 or 20 m and that stability should also be considered.

In addition to the speed of the wind driven surface currents, it is also necessary to consider the direction of water movement. To do this, we must differentiate between currents at the very top of the ocean (wind drift) and the currents at lower levels. Wind drift is defined here as the direction and speed of movement of the top 5 cm or less of the water's surface and is used to clarify the general term "surface current". The term "surface current" as used by oceanographers can mean the net transport direction in a boundary layer (such as the column of water affected by the wind), or relatively shallow layers, or levels, of interest such as 5 m or 15 m. It is generally agreed amongst oceanographers that the wind drift is in the same direction as the gradient wind (Krummel, 1911; Bowden, 1953; Hughes, 1956). The gradient wind is defined as a wind which blows along a constant pressure surface as depicted by the pressure contour lines (isobars) on a weather map. Meteorologists universally agree that the real or actual winds at the surface blow at an angle of 15 to 30 degrees to the left of the isobars. Put another way, the wind drift is 15 to 30 degrees to the right of the measured wind when facing downward. The deviation of wind drift to wind direction is a function of surface roughness. An average deviation of 30 degrees is recommended for the Bering Sea area (Pease, C.H., 1987 pers. comm.) keep in mind that historically, the average height of measured and estimated winds from ships is 19.5 m. If input winds from other elevations are used, an adjustment should be considered along the lines suggested in equation (3).

Finally, if for some reason it becomes necessary to look at current directions below the wind drift level (boundary layer), theoretical calculations by Rossby and Montgomery (1935) indicate a deflection to the right of the wind direction of 41.5 to 53.5 degrees for the latitudes of the Bering Sea. The lower degree value (41.5) relates to a wind of 5 m/s and the upper values to a wind of 20 m/s. The measurement of direction of wind-driven currents in the boundary layer is somewhat more complicated than wind drift because of the time required for the current to become in dynamic equilibrium with the wind speed. Initially, the boundary layer current direction is the same as the wind direction, but continues to rotate to the right, assuming a steady state of wind. Actual current direction measurements indicated angles varying from 0 to 100 degrees from the wind direction for a large number of observations. (All from Wiegel, 1964). At any rate, the angles derived by Rossby and Montgomery appear reasonable. If ice is present, the angle of ice direction should be reduced to that suggested by Wilson and Zubov in subsection 7.3.

6.2 Air Temperature

Climatological temperatures are not an important variable in oil spill trajectory modelling or forecasting. however, they indicate the range which modelers, forecasters, and on-scene-coordinators can expect. Month by month average temperatures and extreme maximum and minimum temperatures can be found in the Alaska Marine Ice Atlas (LaBelle and Wise, 1983). For this atlas, it is adequate to say that the coldest months are February and March, and the warmest months are July and August. Table 6.2-1 depicts temperatures for those months. Also see Figures 3.6-1 through 3.6-3.

Table 6.2-1 Mean and Extreme Temperatures in the Bering Sea.

		Extreme Warm	Mean	Extreme Cold
Coldest (Feb, Mar)	Northern Portion	+1*	-18	-35
	Southern Portion	+6	0	-11
Warmest (Jul, Aug)	Eastern Portion (near mainland)	+18	+10	+3 - 5
	Remaining Portion	+14	+8	+2 - 3

* Temperatures in Degrees Celsius.

6.3 Air Mass Stability

Air mass stability is specifically mentioned here, as well as in other portions of the text, because it is so frequently neglected as an operational tool for the forecasting of winds, ceilings, and precipitation (showers). Stability is the tendency, or non-tendency of an atmospheric layer to overturn or mix. Little mixing of the layers takes place when the atmosphere is stable, particularly over water. If unstable, the lowest layer (for) marine purposes), or atmospheric boundary layer, is more buoyant than the next higher layer. This buoyancy causes the two layers to mix. This condition occurs when cold air is heated by relatively warm water, or warm ice, especially during the winter months.

The height of mixing is determined by the degree of cooling or warming (air-sea temperature difference) and the vertical distribution of temperature in the air mass (vertical temperature profile - VTP). The operator in the field usually has no knowledge of the VTP, but he can easily obtain the air-sea temperature difference which is a good index of low-level stability. A competent meteorologist can acquire both VTP and air-sea temperature differences to provide maximum service to the forecast user.

The stability affects the vertical wind shear which is important for reducing wind speeds to desired reference levels. Because the wind is the main driving force in many predictive models (trajectories, waves, ice movement, etc.) it is important to input correct wind data - both current and forecast winds. Stability also affects ceilings and visibilities as described in Sections 4.7 and 6.5.

6.4 Superstructure Icing

Superstructure icing is the freezing of liquid water on structures. The structures can be on land, or on or near water. These structures on or near water are herein defined as marine structures. This discussion is restricted to superstructure icing on marine structures.

Icing can occur from spray caused by waves hitting the marine structure (freezing spray), spray being blown off the crest of waves (spindrift), freezing rain or drizzle, snow mixed with any of the above, and supercooled water droplets (fog). The main cause of superstructure icing is freezing spray. This is particularly true in Alaska and in the Bering Sea. Although actual reports of superstructure icing in the Bering Sea are sparse, there is considerable evidence that numerous icing events occur. The primary reason for lack of data is the relatively light marine traffic during the winter months. Large ocean going vessels traveling the great circle route from the U.S. Coast to Asia go no further north than Unimak Pass (54.4N 165W) thence westward to the western end of Aleutians. These vessels report occasional icing, however, the most frequent icing area is farther north. Icing reports from farther north, as well as the great circle route area, come mostly from fishing boats, fish processors, tug boats and USCG patrol vessels. Of these, fishing boats contribute the bulk of the data, but in the case of the Bering Sea, it is necessary that an open fishing period, as determined by the North Pacific Fisheries Management Council (MPFMC), coincide with a superstructure icing episode in order to generate data.

Figure 6.4-1 (Wise and Comiskey, 1980) indicates probable areas of icing. Note the lack of icing reports in the Bering Sea but note also the estimation of heavy and extreme icing as indicated by the isolines. Notice numerous reports of extreme icing near Kodiak Island and Shelikof Strait (from longitude 150 to 160). The concentration of reports in that area is because fishing boats, tugboats, and others transit the area from either Kodiak Harbor or Seattle enroute to several Aleutian harbors - mostly Dutch Harbor, where the fishing boats await open fishing periods. Experience and an understanding of atmospheric-oceanic dynamics requires a conclusion that frequent heavy to severe icing occurs in the southern Bering Sea. The northern Bering Sea has much less icing because of the presence of the ice pack which prohibits the generation of ocean waves necessary for freezing spray. Special mention is made here that the Wise-Comiskey estimates are too low for any vessel with the wind on the beam or forward of the beam.

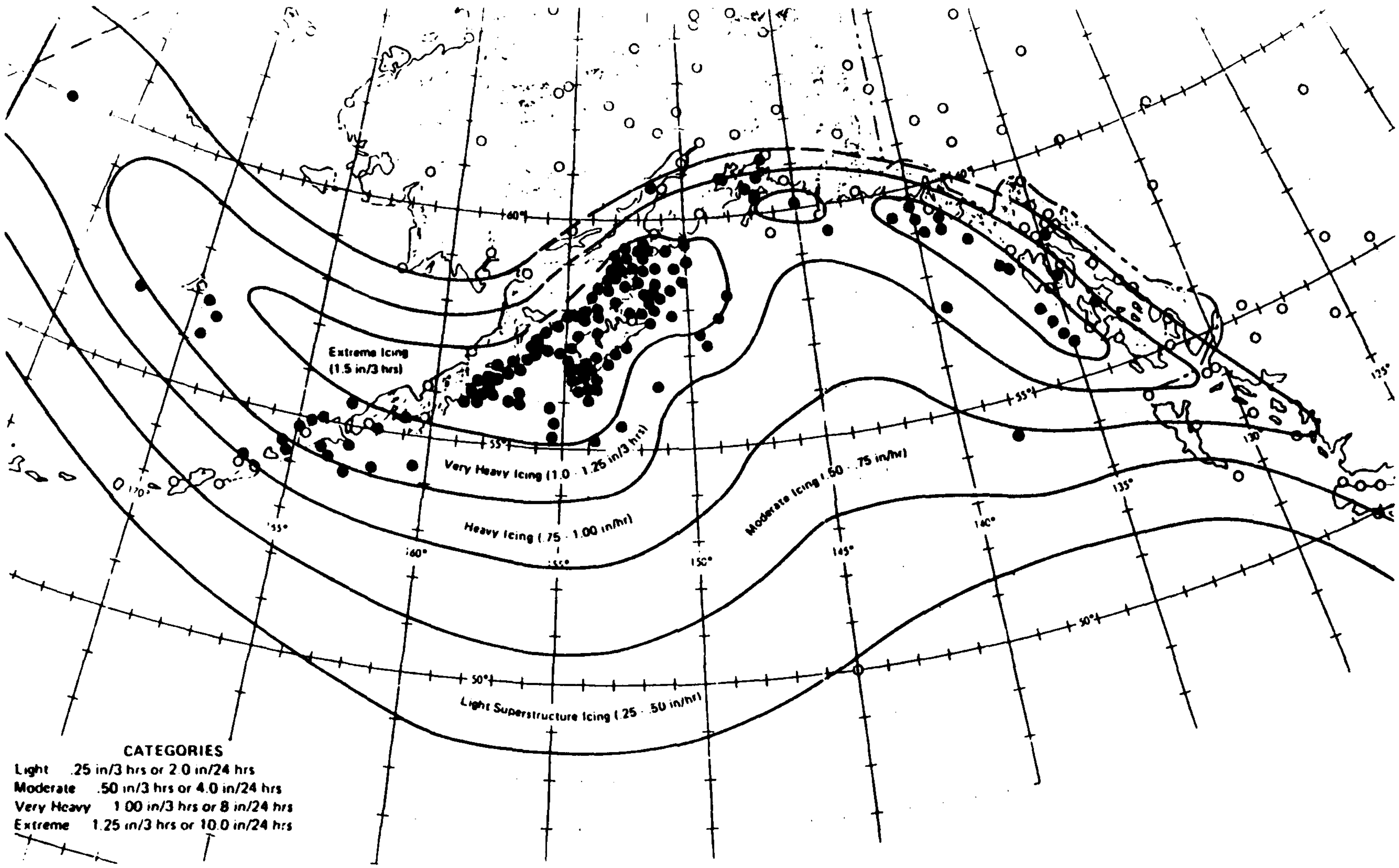


Figure 6.4-1. Estimated areas of icing in the Northeastern Pacific Ocean and the Bering Sea. (Wise and Comiskey, 1980)

In 1985, Taiyo Fishery Co., Ltd. translated a number of Japanese and Russian superstructure icing studies from Japanese and Russian into English (Taiyo, 1985). Many of these studies document superstructure icing under conditions identical or similar to those which occur in the southern Bering Sea and other areas of Alaska.

The file on superstructure icing research in North America is quite small. Canadian researchers (Stallabrass, 1980; Lozowski and Gates, 1984; and others) spent considerable time and resources investigating and developing mathematical and physical superstructure icing models. Their major problems were the lack of data and especially the lack of quality data from which they could verify, or tune, the mathematical models. Consequently, models were derived, but nobody could determine how well they worked.

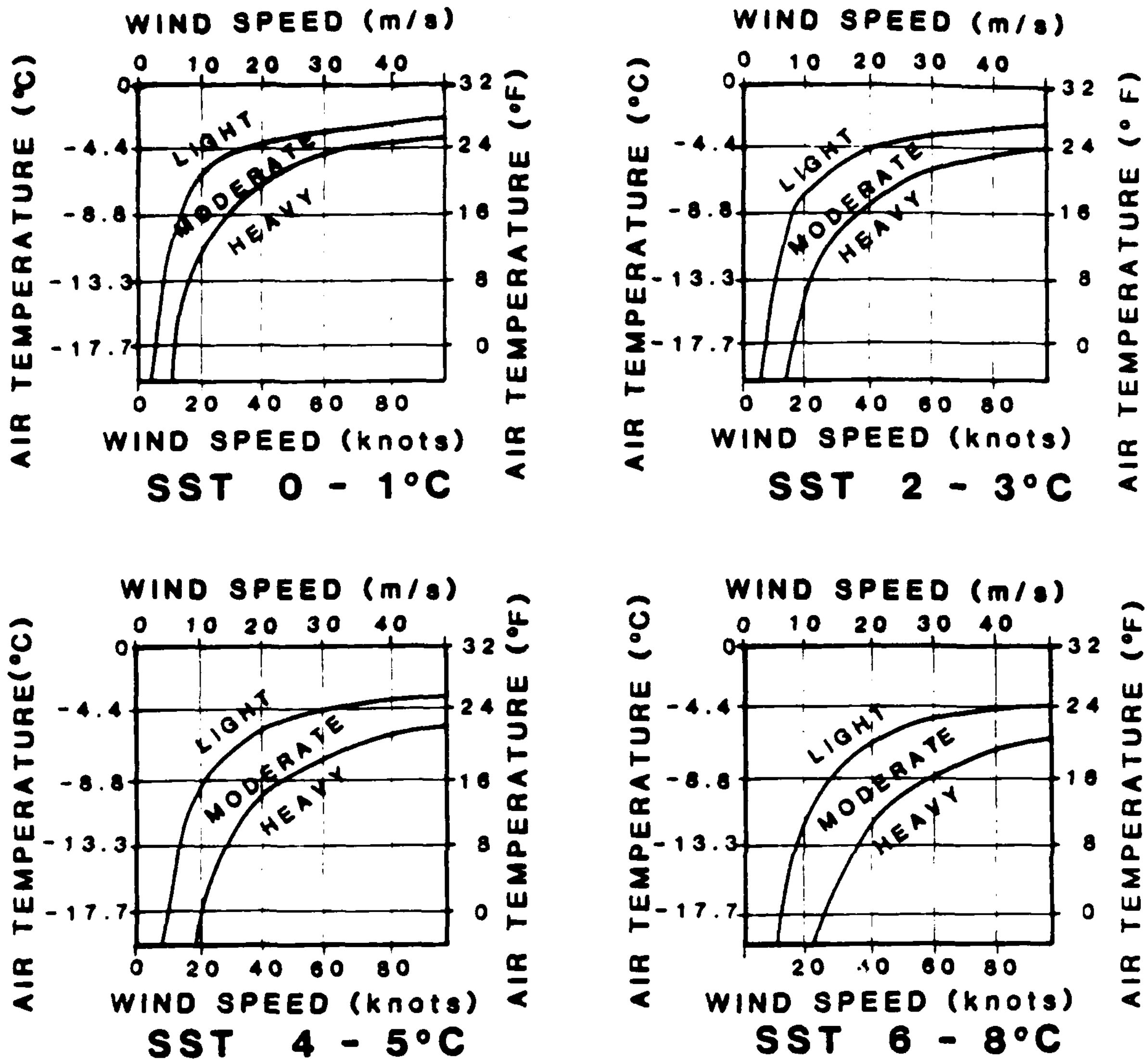
In 1980 Wise and Comiskey made an attempt to compile a data base and concluded that resources were inadequate to obtain a quality data base. Subsequently, they adapted, for use in Alaska, nomograms derived by a German meteorologist (Mertins, 1968), based on Atlantic trawler data. A few years later, Comiskey et al., 1984, compiled a set of data from ships and boats operating in Alaska waters. New superstructure icing rates were suggested that more than doubled the past forecast rate of ice accumulation. Overland (1985) developed, from the data, an algorithm for the prediction of superstructure ice which is defined as the maximum icing rate likely to be encountered by a ship or boat which is moving into the wind. This is, not running before the wind or taking other evasive action. Overland's algorithm forecast three times the amount of icing indicated on the preceding Wise-Comiskey-Mertins' nomograms. The difference is explainable in that the Mertin's data must have included a large number of downwind cases. That is, many of the trawlers were running downwind during icing episodes, which one might expect.

At any rate, Pease and Comiskey (1985), using the Overland algorithm, developed nomograms for the prediction of potential superstructure icing. The Comiskey data set was also published in the same paper. The nomograms developed are shown in Figure 6.4-2. These nomograms are recommended for forecasting superstructure icing rates in Alaska.

The interpretation of the forecast rates from the nomograms requires some thought by the user. For instance, a forecast of heavy icing with low wave heights means little to a large ship because the freezing spray may be well below the main deck line, and the center of gravity of the ship is not significantly affected. However, with heavy seas, spray may come over most of the ship and freeze on the superstructure, thereby significantly affecting the ship's center of gravity.

With surface borne equipment of small size or low freeboard, icing can be heavy with low choppy seas if spray is generated. For instance, a small aluminum boat of 5 - 6 m could experience heavy icing in seas of 0.3 - 0.4 m if running into the wind. Booms and skimming equipment could experience similar problems, although to a much lesser extent on the booms because of their relatively stationary position. However, the booms could lose some of their buoyancy with ice loading, or they may roll if top heavy with ice. These factors might be considered in boom design and use.

In conclusion, superstructure icing is a function of the generating phenomena (wind, temperatures and seas) as well as the characteristics of the icing targets (ships and equipment). The characteristics of targets are size, configuration, heading, percent of heated surfaces, sensitivity to wave action, etc. Some of the above can be collectively defined as the spray characteristics of the target. For instance, each vessel, class of vessels, or equipment has its own signature spray characteristics and these spray characteristics should be



Icing conditions for vessels heading into or abeam of the wind.

Light icing - Less than 0.7 cm/hr (0.3 in/hr)

Moderate icing - 0.7 cm/hr (0.3in/hr) to 2.0 cm/hr (0.8 in/hr)

Heavy icing - Greater than 2.0 cm/hr (0.8 in/hr)

SST - Sea Surface Temperature

Figure 6.4-2. Nomograms for prediction of potential superstructure icing rates. Potential is defined as the maximum icing rate likely to be encountered by a ship or boat.

considered when operating in areas of possible superstructure icing. When inputing wind speeds into the superstructure nomogram, take care to rectify the reported wind as described in Section 6.1 - Real Winds.

6.5 Flying Conditions

Flying conditions in the Bering Sea contain similarities to and differences from other areas. The prime differences are caused by the vast expanse of cold water in the summer which can cause extensive and persistent low ceilings and visibilities. During the winter, conditions are extremely variable with the variability compounded by relatively warm water (usually) and the existence, areal, extent, and character of the ice pack. Topography is not a major factor although it must be considered at times.

Ceilings and visibility are the major consideration in flight planning. Normal and predictable variations occur with identifiable atmospheric processes such as frontal systems and cold air masses. Conditions tend to deteriorate when fronts approach, and improve as the front passes. There are exceptions such as after a warm front passes, and before the trailing cold front passes, the ceilings and visibilities in the warm sector may be consistently low, even with brisk winds. When a cold air mass is situated over the Bering Sea, showers are common. Particularly unique are brief snow showers from cumulus clouds with a vertical rise of only 5 to 7 thousand feet (bases 3 to 5 and tops 10 to 12 thousand feet). These snow showers are usually too small and brief to affect operations. Of most significance is the extensive fog and low stratus that forms over the Bering Sea during the summer months - mostly July and August. These conditions occur when the air is colder than the water, when the air mass is stable, and when winds are light. They will frequently occur when weak to moderate high pressure exists over the Bering Sea. Cloud tops are usually less than 3,000 ft. When this occurs, aircraft operations are severely restricted and the condition sometimes persists for weeks. Occasionally, low ceilings and visibilities will exist when the SST is a few degrees warmer than the air. However, the warmer SST tends to lift the ceiling and improve the visibility. When the sea surface temperature is 2°C or more warmer than air temperature at the surface, conditions are frequently flyable at low levels (below 500 to 1000 ft). Before embarking on over the water low level flights, it is advisable to compare the sea and air temperature profile of the atmosphere along with the SST. A competent meteorologist can accurately predict the ceiling and visibilities.

Wind in the Bering Sea has no unusual characteristics because of the lack of topographic effects. Because of the large storms that move into or near the Bering Sea, and strong high pressure areas that develop over Alaska and Siberia, strong and persistent winds occur - particularly during the fall and winter months. Winds of hurricane force rarely occur. Winds at landing sites are generally predictable.

Turbulence over the Bering Sea is mostly storm related. It can be moderate to severe near strong cold fronts or sharp troughs aloft. This type of turbulence is no different than any that might be encountered elsewhere in North America. Turbulence associated with cumulus development is much weaker than in the contiguous states except when the cumulus are part of an advancing code front. Thunderstorms over the Bering Sea are rarely, if ever, reported, and if reported are most likely to occur in winter in connection with cold air advection aloft.

Icing with frontal systems is no different than might be expected over the contiguous states. If anything, it is probably less because of the lesser water availability in the atmosphere due to colder atmospheric temperatures. Reports of freezing rain are very rare. Reports of freezing drizzle are more common, but the freezing drizzle tends to come mostly from low stratus (tops below 3,500 ft) in the winter time. The freezing drizzle, low stratus, and low level aircraft icing occur when winds are light and the liquid water droplets are cooled well below the freezing point (supercooled). A number of lives have been lost when pilots or forecasters ignored reports of freezing drizzle under, and in, low stratus.

Tables 6.5-1 through 6.5-4 show statistical summaries of atmospheric variables effecting flying. See also Figures 2.6-19 through 2.6-30.

6.6 Sea Ice

Atmospheric conditions (wind, temperature, and vapor pressure) are the prime factors for determining sea ice extent and character. Other factors are sea surface temperature and tides, however, both are relatively constant compared to the atmospheric variables. In short, ice is formed most rapidly when very cold dry air is moving rapidly over cold water. Because the water temperature is conservative (changes little from season to season and day to day), the formation of ice is largely a function of the weather. The weather varies considerably from winter to winter consequently the ice also varies considerably.

The normal and best ice producing situation is when cold dry air blows from interior Alaska to the central Bering Sea. A classic example is shown in Figure 7.1-2. The air is capable of freezing water until the wet bulb temperature of the air is heated above the freezing level of the water. The air, of course, is heated by the water as it moves over the water. The air is also cooling the water at the same time. Along some line a dynamic equilibrium exists. The equilibrium line may move seaward or landward and the ice edge will follow it. It is a

TABLE 6.5-1. Cumulative percent frequencies of ceiling heights and visibiities for two hourly time pairs (U.S. Naval Weather Service, 1970).

NUNIVAK AREA

January to October
59N to 72N and AK Coast to 171W

Ceilings (ft)		<150	<600	<1000	<1000	
Visibilities		<50yd)	<1mi	<5mi	>5mi	OBS
Hours	00&03	10.5	16.6	32.2	39.5	488
(GMT)	06&09	12.8	19.4	32.2	35.0	391
	12&15	19.3	26.8	42.2	33.6	336
	18&21	13.8	23.8	42.3	33.5	400
				TOTAL OBSERVATIONS		1615
Ave. Pct.		13.7	21.2	37.3	35.7	

The above data was obtained from ships within the areas designated.

TABLE 6.5-2. Cumulative percent frequencies of ceiling heights and visibilities for two hourly time pairs (U.S. Naval Weather Service, 1970).

ST. MATTHEW AREA

January to September
59N to 72N and 171W-178W

Ceilings (ft)		<150	<600	<1000	<1000	
Visibilities		<50yd)	<1mi	<5mi	>5mi	OBS
Hours	00&03	20.4	29.5	45.2	37.4	431
(GMT)	06&09	24.0	32.0	49.4	35.7	350
	12&15	32.4	39.3	54.0	26.0	346
	18&21	26.8	36.0	54.2	32.0	406
				TOTAL OBSERVATIONS		1533
Ave. Pct.		25.6	34.0	50.6	33.0	

The above data was obtained from ships within the areas designated.

TABLE 6.5-3. Cumulative percent frequencies of ceiling heights and visibiities for two hourly time paris (U.S. Naval Weather Service, 1970).

ST. LAWRENCE AREA

February to September
62N to 66N and AK Coast to 172W

Ceilings (ft)		<150	<600	<1000	<1000	
Visibilities		<50yd)	<1mi	<5mi	>5mi	OBS
Hours	00&03	7.7	16.1	25.4	35.2	1189
(GMT)	06&09	7.2	14.7	27.6	33.5	1129
	12&15	9.8	15.7	26.9	34.4	1066
	18&21	10.9	18.5	31.6	32.8	1172
				TOTAL OBSERVATIONS		4556
Ave. Pct.		8.9	16.3	27.9	34.0	

The above data was obtained from ships within the areas designated.

TABLE 6.5-4. Percent frequency of occurrence of selected ceiling and visibility thresholds derived from hourly observations from St. Paul Island.

ST. PAUL ISLAND

		Visibilities			
		>0	>1/4	>1	>5
Ceilings (ft)	200	96.7	95.8	89.8	73.0
	600	81.5	81.2	79.6	70.3
	1000	69.7	69.4	68.4	63.1
	5000	22.9	22.8	22.5	21.9
			TOTAL OBSERVATIONS		91788

The above is abridged from the revised uniform summary of surface weather observations. Estimated time of latest St. Paul summary is 1972.

complicated process for which a variety of equations exist. However, all equations require initialization (a starting point). The simplest way to start is to move cold air over cold water and apply an equation. However, when ice begins to form, the equations begin to err, or at least become very complicated. As the ice thickens, it begins to act similar to a land mass with different rates of heat exchange. In recent years, the Pacific Marine Environmental Laboratory (PMEL) developed algorithms for predicting the growth of sea ice in the Bering Sea. The sea ice growth model, using the algorithms, is run daily on the National Weather Service (NWS) computer in Camp Springs, Maryland. The computer output (map) is available through the NWS Weather Facsimile System. The maps along with visual reconnaissance and pictures from orbiting satellites should be used by the OSC and his/her staff in the decision making process. A more extensive discussion of sea ice can found in Section 7.0

6.7 Storm Surges

The most recent and most complete published literature about storm surges for all of Alaska is entitled Storm Surge Climatology and Forecasting in Alaska by Wise, Comiskey, and Becker (Wise, et. al., 1981). The publication was the result of an extensive data search which in turn generated a storm surge forecast procedure suitable by field personnel and local National Weather Service (NWS) forecast offices. The following discussion is built upon the 1981 publication with added details and refinements applicable to this atlas.

For oil spill planning purposes, storm surges will be considered only as coastal phenomena. The Bering Sea atlas coastal area extends from the northwestern portion of Kuskokwim Bay (Cape Avinof) to the southern portion of Norton Sound (Yukon Delta). Within that area, three discrete coastal sectors must be considered for storm surge purposes. The three sectors are 1)

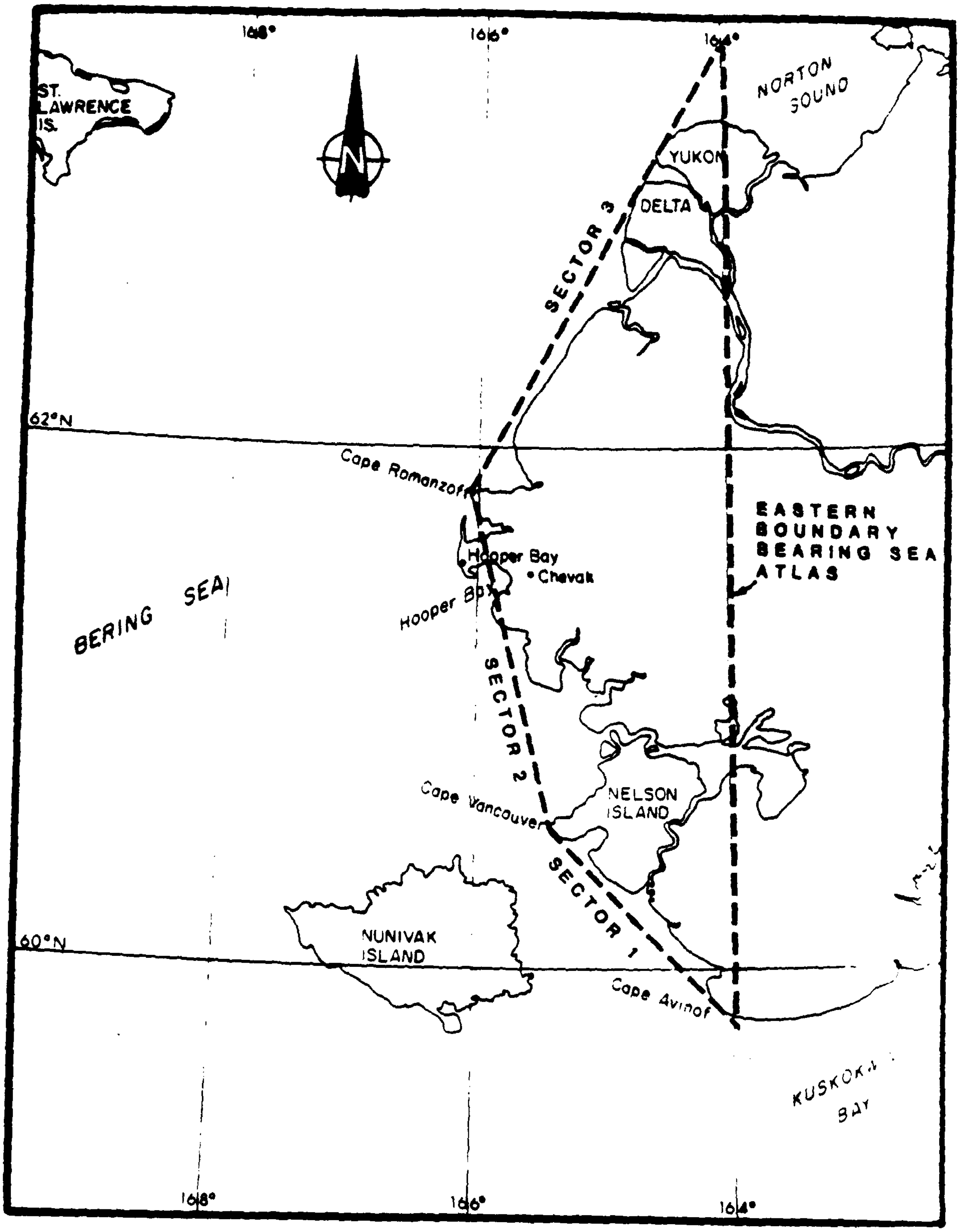


Figure 6.7-1. Dashed lines indicate three different storm surge areas as determined by general coast orientation and topography.

Cape Avinof to Cape Vancouver; 2) Cape Vancouver to Cape Romanzoff; and 3) Cape Romanzoff to the Yukon Delta. See Figure 6.7-1. The sections are labeled for forecast purposes. See Appendix B.

Although data is sparse in the three sectors, storm surges to 3.7 m can be said with considerable confidence to have occurred in all three sectors. Surges to 3.7 m have been reported both south and north of the three sectors and flooding well above the river bank has been reported inland as far as the village of Chevak which is 26 nmi east of the village of Hooper Bay (along the outer coast) and about 10 miles by river from the high tide level in Hooper Bay. Chevak is located at 61° 30′ 40" N 165° 35′00"W. In addition to documented evidence of coastal flooding because of storm surges, a study of the contentinental shelf bathymetry and the onshore topography strongly indicates the likelihood of storm surges and coastal flooding. See Figures 2.1-1 and 2.2-1.

Before going further, a few definitions are in order:

1. Surge -

   The height of the ocean's surface above forecast tidal levels.

2. Primary surge -

   The surge that directly results from atmospheric winds.

3. Secondary surge -

   The surge that results from gravity acting upon anomalous sea heights created by primary surges.

4. True Wind Direction -

   The true direction from which the wind is blowing. A south wind is from 180°.

5. Relative Wind Direction -

   The direction from which the wind is blowing relative to the general directional orientation of the coastline. For instance, if the coast is oriented from southeast to northwest, the coast to the left, when facing seaward is 000°, straight ahead (seaward) is 090°, and the coast to the right is 180°.

6. Fetch -

   An area in which the wind direction and speed are relatively constant.

Other, or more refined definitions, may be found in Appendix C.

Storm surges that cause flooding are caused by winds associated with strong atmospheric storms. Surge heights are measured or forecast with respect to predicted water levels (tides). A storm surge forecast of 2 m would therefore be 2 m above the predicted tide height. Storm surges which are coincident with high tides have the greatest impact along the coast. In addition to flooding, there is increased wave activity because of the deeper water along the coast. The types of coasts most susceptible to surges are those with shallow water offshore and low lying land along the coast. See Figures 2.1-1 and 2.2-1. There have been no reported surges occurring along the shores of islands in the Bering Sea. This is understandable because of the relatively deep water around the islands. However, even with lack of observations or mechanical recording devices, it is likely that surges to 1 m occur as have been measured along similar coastlines elsewhere in Alaska.

Surges occur when the wind causes a net transport of water to the right of the wind direction in the layer of water affected by the wind (the boundary layer). The angle of deflection to the right may be as much as 100° (Stommel, 1954). However, the angle of deflection may be considerably less because of the numerous variables involved such as latitude, duration of wind speed and direction, depth of ocean, water density differences, and others (Wiegel, 1964). With favorable wind directions, the surge height increases along the coast and a gravity induced return flow develops along the ocean's floor. When the return flow equals the wind induced flow, a state of equilibrium exists and water levels remain constant. When the wind decreases or changes to a less favorable direction, the return flow exceeds the wind induced flow and the water level drops. It is also possible to get negative surges (below predicted tide levels) with strong offshore winds. Negative surges are usually less than 1m. Favorable wind directions for positive surges are given in Appendix B.

Also of interest is the subject of secondary, or gravity, surges. For instance, when the north coast of Kuskokwim Bay is being subjected to strong southeasterly storm surge winds, the south coast is being subjected to strong offshore, or negative surge, winds. However, the south coast will not have a negative surge. It will have a positive surge. As the water heights increase along the north coast, an anomalous slope to the ocean's surface is created. The force of gravity trying to return the ocean's surface to equilibrium causes a flow toward the area of lower sea surface heights. When the sea surface slope exceeds a given value, the gravity induced flow exceeds the wind drag flow, and a positive surge begins in the "negative surge" area. This type of surge is herein defined as a secondary surge. In summary, if a positive surge of any significance (1m or more) occurs in any relatively small bay, there will be a surge in the entire bay. However, it is important to note that for oil spill mitigation purposes, it is only the windward shores that may be affected because the oil travels with the surface current (wind-drift) which is in approximately the same direction as the gradient wind. Finally, do not confuse ocean currents or net transport currents with "surface currents" as is used here. For purposes of this atlas, we define surface current as the top 5 cm or less of the ocean's water column.

The forecasts of storm surges involves factors other than wind speed and direction. A suggested procedure is shown in Appendix B. The National Weather Service (NWS) Forecast Office in Fairbanks monitors the Bering Sea area rather closely because of surge history in that area. The NWS can be contacted directly during an oil spill episode, but it may be more effective to hire a private meteorologist to interface between the NWS and the OSC for improved communications and to do specialized forecasts if necessary.

7.0 SEA ICE

7.1 Ice Coverages

Sea ice coverages (averages), are illustrated on Figure 7.1-1. The ice edge (dashed lines) and the ice coverage boundaries (solid lines) represent the 50 percent probability lines. You should expect the ice edge or designated concentration to be on one side of the line 50 percent of the time and on the other side 50 percent of the time. Anomalous weather conditions can cause very anomalous ice coverage conditions. Figure 7.1-2 shows the ice pack in one of its most organized conditions with the ice pack almost solid and the ice edge very close to its climatological average. However, Figure 7.1-3 shows that the ice edge can vary from 55° to 62° N in March. In addition, the pattern of coverage can vary significantly. An intense storm with temperatures above -1°C can cause extensive disruptions in ice coverage. Another photo taken March 27, 1980 (Figure 7.1-4) shows the effect of one or more storms in addition to a different type of "climatological" winter than in Figure 7.1-2. Climatological or average ice condition knowledge has little value for real time spill episodes, but may have value for pre-spill planning.

Looking at Figure 7.1-2 more closely reveals polynya areas south and southwest of the Seward Peninsula, St. Lawrence Island, St. Matthew Island and Nunivak Island. One might suspect open water in those areas. However, note the streamer lines of low clouds in a convective condition in the southeastern Bering. Obviously, very cold air is blowing over the ice pack and into the Bering Sea and Pacific Ocean. This means that new ice is forming very rapidly in the polynya areas. Ships could manage in the polynya area and the threat of superstructure icing is minimal due to

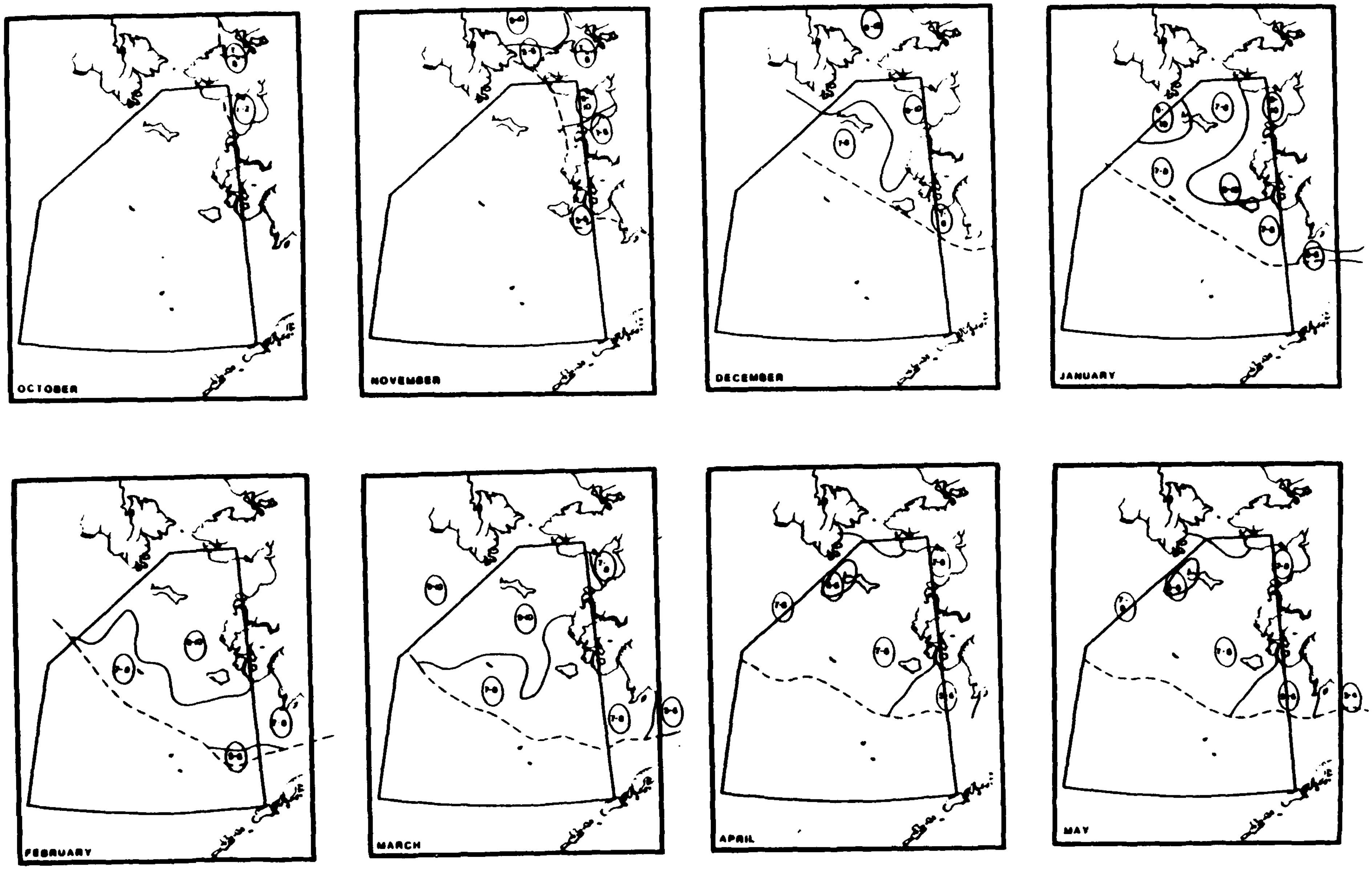


Figure 7.1-1. Dashed lines indicate the most probable position of the ice pack edge. Numbers indicate ice coverage in tenths (from LaBelle and Wise, 1983).

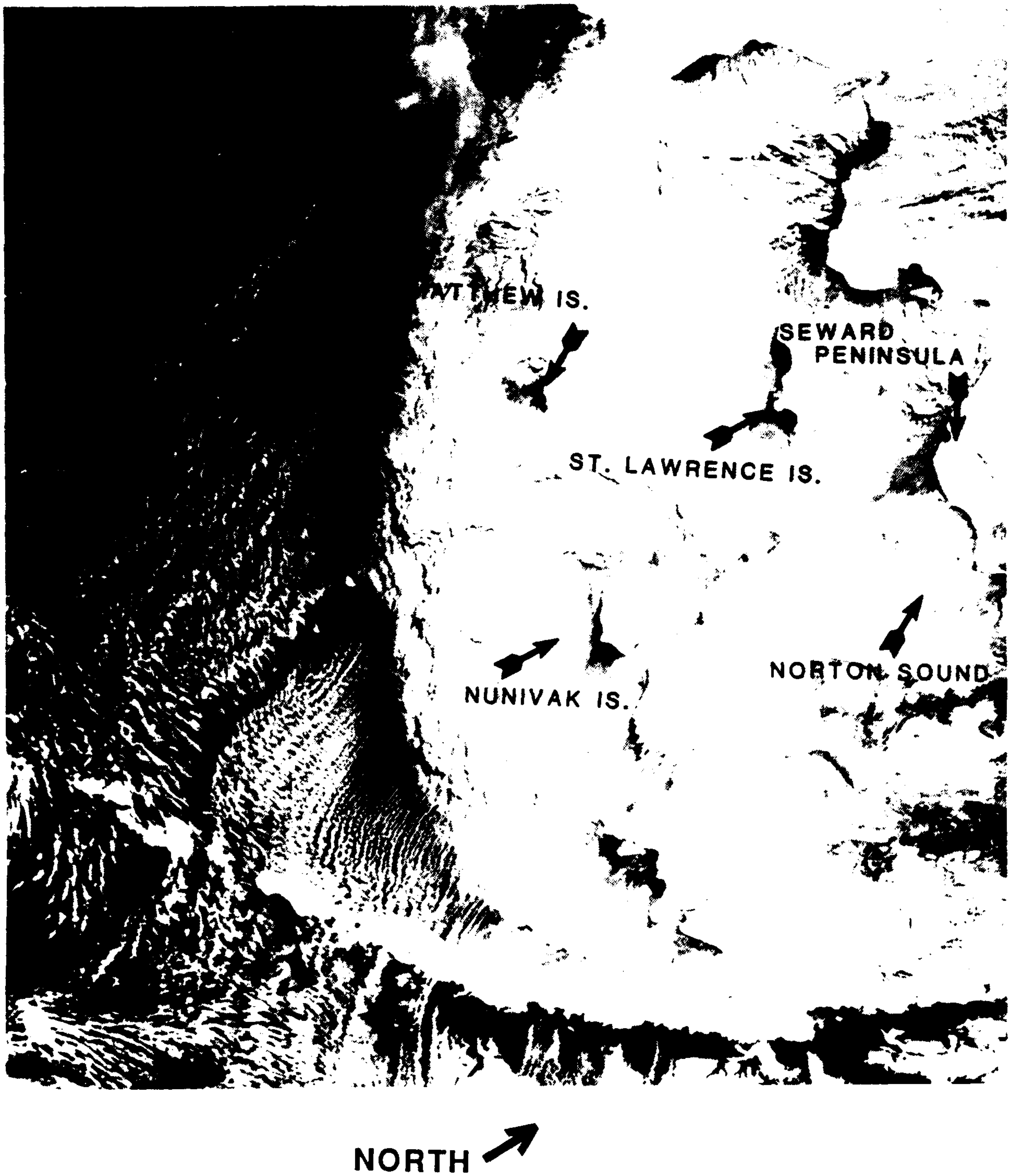


Figure 7.1-2. Photo of Bering Sea ice pack March 21, 1975 with ice coverage coincident with climatological averages. Infrared photo from NOAA orbiting satellite (from NORTEC files).

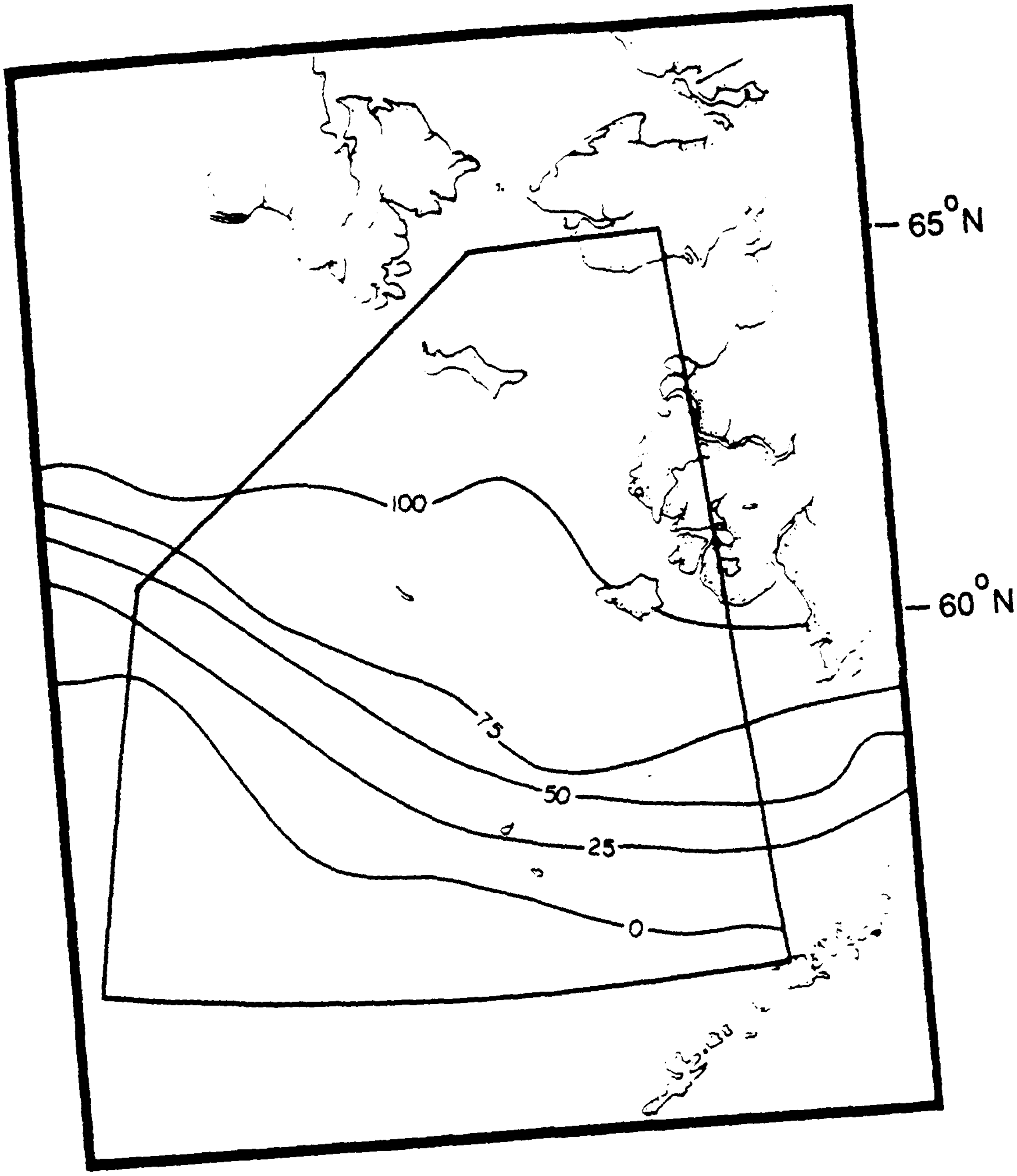


Figure 7.1-3. The leading edge of the Bering Sea ice can occur anywhere between lines labeled 0 and 100. The line numbers indicate probability of ice edge occurring in March at any particular line location.

Figure 7.1-4. A March 26, 1980 photo of the Bering Sea shows the nearly complete disruption of the normal Bering Sea ice pattern either by an anomalous climatological winter and/or one or more severe storms with warm air temperatures. Infrared photo from a NOAA orbiting satellite (from NORTEC files).

little or no wave action. Conversely, the threat of superstructure icing is very high in the central and southeastern Bering as well as south of the Alaska Peninsula all the way eastward to the north-central Gulf of Alaska.

7.2 Ice Character

Ice can occur in wide variety of forms (pans, flows, etc.), internal conditions (temperature, entrapped air or water, and salinity), and thickness. Flows range from several km in diameter to less than 1m (pancake ice). The edges of the flows will be crushed to varying degrees depending on their history. Because of compressional or shearing forces within the ice pack, many of the ice flows are crushed, or reduced to rubble. When the rubble predominates, the area of rubble is called a rubble field. A rubble field wherein the rubble has frozen together is called a consolidated rubble field and becomes an entity similar to an ice flow but with different internal characteristics. A further discussion of ice character as it relates to shearing and compressional forces is contained in subsection 7.6. The entire spectra of ice characteristics is described in the U.S. Navy-NOAA Joint Ice Center Ice Observers Handbook, 1981.

The objective of this narrative is simply to discuss ice to enhance the feasibility of ship operations in ice (other than specifically designed icebreakers). Briefly a ship will operated with less difficulty when:

1. Operating in a rubble field as opposed to large ice flows even though the rubble field may be thicker.

2. Operating in an unconsolidated rubble field as opposed to a consolidated rubble field.

3. Operating during divergent ice conditions as opposed to convergent ice conditions. Convergence and divergence is discussed at length in subsection 7.4.

4. Operating in "warm"(-1 to -7°C) ice as opposed to "cold" (<-7°C) ice.

In addition, ice thickness is critical at certain values depending on variables 1 through 4 and individual ship capabilities. See Figures 8.2-1 through 8.2-10 in subsection 8.2 which show the near maximum ice that can be navigated by a seagoing tug, of 3000 HP, pulling a 100m by 15m loaded barge with draft of 4.2m.

7.3 Ice Movement

Net ice movement is determined by the summation of forces and factors affecting the ice or surrounding water. There are three types of currents (excluding river induced currents) to be considered. The general circulation current is weak and depicts net water transport over a period of time - years. The upper boundary of the water column (sea surface) has current velocities determined mostly by the wind and by the tide. Tidal currents can be significant but because of their oscillatory nature, can be ignored except in the very short term (less than 24 hours). Thus, the primary driving force for ice movement is the wind. One other factor not frequently thought of as an ice movement is air and water temperature. Temperature is a factor when considering the ice edge. If the air is very cold blowing off the ice edge and the water is near or at freezing, new ice will form ahead of the wind-driven ice pack so that the leading edge of the ice pack both moves and grows simultaneously giving a relatively rapid "movement" to the edge of the pack. Conversely, if the wind is blowing the ice into water well above freezing, the ice pack edge will melt thereby retarding the "movement" of the edge.

In addition to the above, the internal drag (ice to ice) of the ice pack is a factor which can range from zero (open pack) to 1.0 (ice movement totally stopped by very close compaction created by contact with shorefast ice, land, or ocean bottom). Various measured wind-ice drag coefficients do not significantly reflect internal drag values; however, for ice that is "allowed" to move with the wind, its movement is quite predictable.

Fortunately, there have been several recent, sophisticated, and definitive studies made of air-drag coefficients over the northeastern Bering Sea (Overland, 1985a; Pease et al., 1983; Macklin, 1983). All of the referenced studies were based on gust probe data collected by NOAA P-3 aircraft in February 1983. In addition, the paper by Overland demonstrates consistency with drag coefficient measurements from other sources, and that drag coefficient values are a function of ice roughness, heat flux, and atmospheric conditions. Drag coefficient-wind correlations indicate that ice will move at a speed of 2 to 5 percent of the wind speed. A single value rule of thumb of 3 percent is reasonable. Tuning of the 3 percent value can be done as follows:

If the ice is smooth and the air is -5°C or warmer, use 2 percent movement. If there is internal stress, use zero to 2 percent.

If the ice is rough and the air is colder than -5°C, use 3.5 percent. If there is no significant internal stress as characterized by visible water surrounding the flows, along with continued roughness and cold air, use 4.5 percent. The most rapid movement usually occurs along the edge of the ice pack, also called the marginal ice zone (MIZ).

The reference level wind is 10m. Winds at different elevations, usually higher, must be reduced to the reference level. See subsections 6.1.2 Real Time Winds.

In summation, the ice will move at 3 percent of the wind speed and at a direction 25 degrees to the right of the wind direction (if wind is northeasterly, ice movement is to the west-southwest). Simple arithmetic shows that a wind of about 30 kts will balance a tidal current of 1 knot with respect to ice movement when the two are directly opposed. However, the wind tends to be persistent while the tides are oscillatory. Thus any persistent wind of more than 5-10 kt will soon create divergent areas along lee coasts and convergent areas along windward coasts. If one were to quantify the convergent condition of ice at any point in time, the lowest limit would be zero with zero ice (open water). The upper limit would be a combination of wind affects, atmospheric pressure, tide affects, topography, bathymetry, and ice pack characteristics. Unfortunately, no attempt has been made to quantify convergence either as a function of one variable or several. However, it is obvious that the upper limit of convergence can be very high and variable. It could be high enough to threaten the structural integrity of ships or equipment, and operators of surface borne equipment should be particularly aware of actual or potentially high convergence areas.

Finally, the sea ice, because of the coriolis force generated by the earth's rotation, moves to the right of the wind direction approximately 25 degrees (Wilson, et al., 1984; Zubov, 1945). Thin ice tends to move at an angle less than 25 degrees but not less than 20 degrees. Thick ice (more than 2m) tends to move at an angle between 25 and 28 degrees (Pease and Overland, 1984).

7.4 Ice Convergence and Divergence

The state of convergence or divergence of the ice pack is very critical to ships, boats, or other equipment operating within the ice pack -- particularly non-ice designed equipment. Convergence and divergence (C and D) also determine, to a considerable degree, the character of the ice pack (roughness, size of flows, etc.). Before discussing the effects of C and D, in non-mathematical terms, convergence is simply defined as "the coming together" of ice within the ice pack. Divergence is defined as "the going apart" of ice within the ice pack. No significant literature has been found to exist on the subject of C and D although the effects of C and D, (ice roughness, leads, etc.) are sometimes documented but usually without reference to ship operations, especially ship operations in first year ice by non-icebreaking type ships or equipment. This is because non-icebreaking ships do not routinely penetrate the ice, even first year ice, and when they do, the operators or personnel have been notably non-productive in generating and documenting observations or data on this subject. It is believed that both Swedish and Finnish navigators have operated routinely for decades in the first year ice of the Bay of Finland and the Gulf of Bothnia but the Swedish and Finnish operations hinge more on brute force (powerful ice breakers) than on finesse (the exploitation of C and D conditions).

The following information, concepts, and opinions documented for this atlas were derived from observations and experiences of Albert L. Comiskey, a member of the NORTEC staff.

The factors affecting C and D are primarily winds and tides. Secondarily are atmospheric pressure, topography, bathymetry, and general macroscale circulation.

In Cook Inlet the primary, most frequent, and most predictable indicator of C and D are the extreme tides (>10m). The Bering Sea tides undoubtedly contribute to the C and D patterns there but the contribution is subtle and less predictable because of the relatively low tidal ranges, generally less than 2m, and current speeds, and the relatively weak tidal currents, generally less than 0.5 m/s. If we neglect for the moment the drag effect of the wind or assume a no wind condition, and little internal ice stress, the ice will move at the speed and direction of the tidal current. Consequently, the ice near shore will be convergent when the tidal current sets on shore and divergent where it sets offshore.

If we have a wind drag force, the ice near shore will be convergent with an onshore wind and divergent with offshore wind. Because the tidal force is periodic and the wind force is variable, both tides and winds must be known to predict C and D. Wind and tide are only the most obvious, available and simplistic parameters. There are other forces affecting C and D in the ocean and the atmosphere but these forces are not systematically available to the OSC or to any vessel operator but must instead be utilized by modelers and forecasters using high speed data processing equipment.

At the time of this writing, there are no operational forecast models that deal specifically with C and D and part of the purpose of this section is to increase awareness of the concept.

Ship operators are particularly directed to Section 8.0 where manifestations of C and D, which can be observed aboard ship, are described. Whether or not ships or boats can operate in first year ice, frequently depends upon the convergent or divergent conditions of the ice.

7.5 Ice Growth and Dissipation

Ice growth can be measured directly in some cases but the normal procedure is to equate ice growth to daily calculated freezing degree days (FDD). FDD is defined as the difference between a representative air temperature and another temperature that represents the freezing temperature of water (0°C for fresh water and near -1.8°C for salt water). The air temperature is normally the mean air temperature as measured at a selected coastal site. Various empirical relationships between air temperature and freezing points have been derived.

One of the oldest and most frequently quoted relationships was developed by Zubov (1945).

$$I^2 = \frac{FDD - 28.61}{1.43} \qquad (1)$$

The equation has been modified to yield ice thickness in inches.

I = ice thickness (in)
FDD = cumulative sum of freezing degree days in Fahrenheit based on water freezing temperature of 0°C.

Why Zubov chose 0°C for arctic ice is not known, but if we rectify the freezing temperature to -1.8°C, more representative of the Bering Sea, the equation takes the following form:

$$I^2 = \frac{FDD - 28.6}{1.26} \tag{2}$$

Equation (2) is now more comparable to Bilello's equation for ice melt (Bilello and Bates, 1962-72).

$$I_M = .12 \text{ WDD}$$

I_M = Ice Melt

WDD = Sum of warming degree days in degrees Fahrenheit using a melting point of 28.8°F (-1.8°C).

There are very significant differences in the two equations. The equation for freezing is non-linear with a logarithmic profile. Simply, this means that the thicker the ice, the slower it grows for each equal increase in FDD. However, Bilello's equation is linear which says that the ice melts at the same rate no matter the thickness. In short, the ice melts more rapidly than it freezes for equal absolute values of FDD and WDD. How much more rapidly? A few calculations yield the following: To freeze and then melt 12 inches of ice would require 2.43 more FDD than WDD; 24 inches would require 3.09 more FDD than WDD; and for 36 inches the ratio is 3.46.

However, to increase the ice thickness from 36 inches to 48 inches requires 1270 FDD. To decrease ice thickness from 48 inches to 36 inches requires only 100 WDD. In other words, ice melts almost 13 times faster than it freezes in the 36-48 inch range.

Both Zubov's and Bilello's equations are simplistic relationships on which considerable improvement could be made. It has been noted that ice in Cook Inlet which we view almost daily during the winter months has been seen to disappear with amazing rapidity with only moderate warming degree days but with strong winds. Transits of the inlet by boat or plane do not find large pile-ups of ice on the windward shores. The ice just seems to vanish. Conversely, the ice build-up seems to follow more predictable rates. Rather than a simple relationship between FDD, WDD, and ice thickness, we feel there is a complex physical relationship involving turbulent heat fluxes both above and below the water's surface, varying vapor pressures, frictional affects, etc. that could more accurately describe ice thickness changes.

The term "ice thickness" requires definition. Ice thickness is described as the thickness an undisturbed flow of ice would have at some point distance from its edge where no deformation has taken place because of compressional forces, or no distorting drag or shear forces have occurred. Thus, in the Bering Sea, it would be very unusual to witness or measure ice thicknesses representative of the sum of the FDD. The two main reasons are: 1) the ice is constantly being subjected to deformation forces; and 2) those floes that develop with no deformation (except along the edge) normally drift westward or southwestward because of the prevailing northeasterly winds during the winter. New ice forms in Norton Sound and in the polynya areas as the old ice moves out with the new ice developing its own thickness regime. Now comes the part that many people do not realize. During mid-winter when cold east to northeast winds prevail, the ice floes become steadily thicker as they move toward the central Bering Sea. This is because the air over the ice is still much colder than the freezing temperature of the water and the ice continues to accumulate FDD and thicken. This movement toward the central Bering Sea is called, by several authors, the conveyor belt system. To complete the simile, the conveyor belt continues to acquire a heavier ice load until the FDD changes to WDD and/or certain other factors contributing to melt, such as warmer water, begin to predominate.

7.6 Shearing and Compressional Forces

Shearing and compressional forces of the ice pack is also defined as internal stress. Anything that causes movement within the ice pack wherein two or more components (flows, cakes, etc.) come in contact creates internal stress. When the ice is divergent, internal stress is minimum and ice deformation is at a minimum. When the ice is convergent, internal stress and deformation is maximum. Within the ice pack, wind and current stress equate to internal stress and when accompanied by convergence cause crushing of the edges of flows, thereby causing the ice to move vertically either downward or upward. The vertically displaced ice frequently becomes consolidated to the ice flow so a characteristic of ice flows, particularly older flows, is that they are much thicker along the edge than away from the edge.

If two flows come together and become consolidated through freezing, a ridge is formed away from the edge of the consolidated flows. The ridge, and keels, of first year ice are not as spectacular as in multi-year ice (the arctic) because of the relative thinness, softness, and lesser areal extent of first year ice in addition to the general lack of macroscale wind and current forces acting on the ice pack. Broad fields of moderate or strong winds over any portion of the arctic can cause internal ice stress in other portions of the arctic. The ridges and keels of first year ice can be thought of as occurring in an array of different forms. For instance, if two relatively thin flows come together, one may be forced under the other (rafting) with no significant "ridging". This merely causes a thickening where the two flows come together. During the winter, the maximum average thickness of the ice pack in mid-winter is considerably less than

1 meter because of the conveyor belt effect. The thinner ice deforms at much lower external force levels with subsequently less spectacular resultant ice shapes.

Also within the ice pack, flows of no great internal strength which are repeatedly subjected to alternating convergent and divergent forces, such as from tides, tend to break up into small pieces. These small pieces when close together form a rubble field. If for some reason, such as a change in air temperature, the rubble field freezes together, it is called a consolidated rubble field or a consolidated rubble flow which may acquire a flow-like identify, but with unique internal and external characteristics in both appearance and strength. It is suspected that rubble and rubble fields are more prevalent near land masses and especially along the coasts with the highest tidal ranges. In general, the largest flows of most strength will be found in the northern Bering Sea (Potocsky, 1975).

Major shearing and compressional forces occur along the edge of the shore fast ice. During the winter the shorefast ice remains attached to the shore. If for some reason it separated from the shore, it merely joins the moving ice pack. The significance of continuity of shorefast ice is that it is not part of the conveyor belt system. Its thickness is determined by freezing degree days (FDD, see Section 7.5) and continues to thicken as long as FDD continue to accumulate. The end result is that shorefast ice becomes thicker and stronger than the moving pack ice as winter progresses. Thus when the pack ice moves into the shorefast ice, the shorefast ice normally holds firm thereby creating considerable stress along its edge. If the shorefast ice is relatively thin, rafting or ridging resulting from convergence, may occur. In either case, the shorefast ice may continue to build seaward with evidences of rafting and ridging now internal to the shorefast ice. In short, shorefast ice does not have a uniform thickness. Its maximum thickness from accumulated freezing degrees is estimated to be between 0.6 and

1.5 m. However, it is thicker in places because of past shear and compressional forces. Shorefast ice thickness and horizontal extent depend in a large part to (1) FDD, (2) range of tides, and (3) bathymetry (shallow water along the coast).

In summary, internal stress occurs within the ice pack and determines much of the character of the ice pack. The greatest stress occurs along the shorefast ice edge but the character of the shorefast ice is more dependent on FDD and ice-edge forces than on internal stress.

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8.0 SHIP AND EQUIPMENT OPERATIONS IN FIRST YEAR ICE

8.1 Background Information

This chapter does not imply that the Coast Guard recommends ship operations in first year ice in other than icebreakers and vessels with reinforced hulls. The information is presented for vessels that find themselves inadvertently trapped within first year ice.

In the past, mariners did not find it necessary to operate in first year ice and it was generally considered that effective operations in multi-year ice was impossible. However, during the last decade the more adventuresome mariners have successfully experimented with operations in first year ice. Now with the advent of fossil fuel exploration and development, and supportive activities, the subject of operations in first year ice is getting more and more attention.

What about present year ice operations? We know that a German trawler processor, the Friedrich Busse, has trawled within the Bering Sea ice pack at least five winters and has been trawling in ice since construction in 1969 (Pennington, 1986. Pers. Comm.). We know that both the Japanese and Russian processor-trawlers and cooperative work boats, including other trawlers, routinely penetrate the Bering Sea ice pack. Both NOAA ships and Coast Guard ships operate in the ice pack. The Finnish and Swedish icebreakers and other ships have operated for decades in the Bay of Finland and Gulf of Bothnia. Bulk cargo carriers have transited Cook Inlet every week each year since the early 1960s. Rig tenders operate in Cook Inlet year round. Finally, boats of less than 3500 HP operated successfully in Cook Inlet the entire 1984-1985 winter when ice to .75 m (undisturbed flows) was encountered.

All of these except the 1984-1985 tugboat (Pacific Western Lines) operations, were conducted without benefit of concepts of convergence or divergence, drag coefficients, etc. The primary modus operandi is to overcome the ice with horsepower and if that fails, wait until the ice condition changes enough to allow movement and/or continued operations. Little has been learned about improving ice operations through experience because the ship operator experiences only a tiny portion of the entire ice pack and is generally unaware of the dynamic mesoscale and macroscale forces at work. In short, the present approach is limited to horsepower and patience with little or no scientific finesse. Hull strength has been given little attention and at this time does not appear to be a problem. However, the subject of hull strength should not be ignored. Formal study is recommended, but even a survey of types of hulls that have been subjected to first year ice stress would be quite informative. A variety of boats and small ships have been stopped or trapped by ice in Cook Inlet over the past two decades.

8.2 Operating Recommendations

First and foremost, stay out of convergent area (see subsection 6.4). First year ice with undeformed thickness of 1 m or less and deformed thicknesses of 2 m or less can be navigated in non-convergent areas. See Figures 8.2-1 through 8.2-10 for examples of a tugboat navigating ice thickness of 1 to 2 m. Keep in mind that thicknesses refer to the thickest flows. In non-convergent conditions, ships can usually avoid the thickest flows and penetrate and split the thinner flows. Figures 8.2-1 through 8.2-10 depict almost maximum thickness and congestion that a sea-going tug is capable of handling. Most first year ice is much less imposing.

Figure 8.2-1 Aerial view of pack ice showing effects of convergence. Light to moderate.

Figure 8.2-2 Aerial view of pack ice about 2 hours after tidally induced divergence has occurred. Note sun glint from open water.

Figure 8.2-3 Aerial view of pack ice about 4 hours after tidally induced divergence has occurred. Note large open area along coast (upper portion dark area) and large mostly open area in lower portion of photo. Heaviest ice is concentrated over deep channel where convergence is expected during ebb tide.

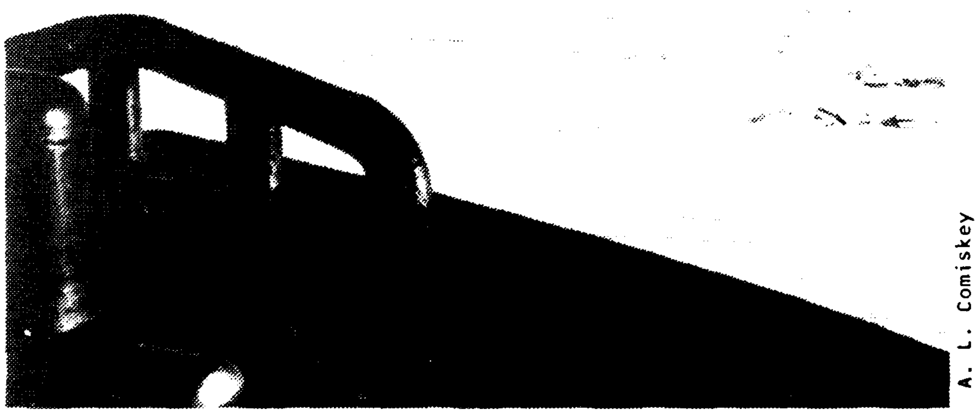

Figure 8.2-4 Tugboat is entering known convergent area, but ice is thin and relatively soft. Thickness of undisturbed flow (smooth flow) is 25 - 30 cm.

Figure 8.2-5 Tugboat is entering thicker ice (0.3 to 0.6m, but it is only moderately consolidated. Note small area of open water, upper left, indicating the first signs of divergence.

Figure 8.2-6 Tugboat is entering thicker portion of ice pack, but the pack is mostly consolidated rubble. That, along with divergence, allows the tug to continue. Thickness of consolidated rubble is about 1m.

Figure 8.2-7 Pack is now at its thickest. Tug must actively avoid consolidated flows. The tug is now headed from a convergent area to a known divergent area. In this figure, divergence has been occurring about 2 hours. Undisturbed flow thickness is .74m. Rubble varies from 1m to 3m.

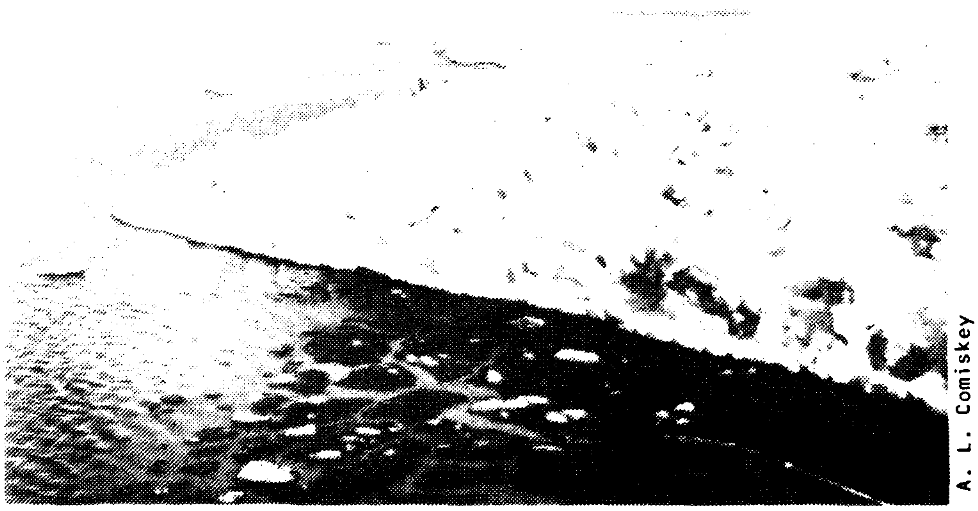

Figure 8.2-8 Tug has passed through heaviest ice and has reached an area that has been undergoing divergence about 3 to 3.5 hours. Tug is now able to move in open water most of the time. Thickness of consolidated rubble flow in foreground is 1.5 - 1.7m.

Figure 8.2-9 Tug breaks out into large lake-like polynyna area with only 3 - 5 cm of new ice and a few stamuki. There is little doubt that the eastern portion of the Bering Sea would at times resemble this portion during mid winter.

Figure 8.2-10 Tug has left polynyna area and entered new light flow ice again. Note how ice is moving away from ship's track indicating divergence.

Be careful following leads. Under convergent conditions, they can close rapidly. It is sometimes necessary to leave a lead that appears good to navigate toward a known or suspected divergent area.

Avoid headlands on the flood tide when the tide tends to push the ice up against the shore and particulary on one side of the headland or another depending on the direction of the tidal current.

Avoid windward coasts if the wind is over 4-5 knots.

Do not be discouraged by thick ice enroute to your destination. The ice could range from light to non-existent at the destination. See Section 7.1 (Ice Coverage).

Prior to and during transit of the ice, assemble and integrate all available weather information in order to determine probable convergent and divergent area (including polynyas).

Compute the tides in advance for any place along the projected route of the ship. A change from convergence to divergence, or visa versa, frequently takes place at tidal change time even though the visual effects of condition change may not be obvious for 1 - 3 hours after tidal change.

The ship is in a convergent area if the ice closes in rapidly astern after forward passage through the ice. If the open water created by the screw(s) widens behind the ship, it is in a divergent area. If the open water behind the ship closes very slowly, the ship is in a neutral area. The change from convergence to divergence, and visa versa, can be detected by observing the character of the trail of the ship.

Rubble flows are less resistant to ship movement than undisturbed flows of equal thickness.

8.3 Recommendations for Improving First Year Ice Operation Concept

Most ships that have penetrated first year ice have done little to enhance our understanding. Icebreakers are designed to cope with multi-year ice and tend to neglect data relating to first year ice. When in the ice pack, fishing vessels tend to stay near its edge where heavy convergence is unlikely. Rig tender and tugboat operators give little thought to the overall forces at work. In addition, no one has laid any comprehensive or systemized requirements on any operators to submit ice information. It is our view that one or two simple studies in a discrete area such as the Bering Sea could greatly accelerate the knowledge and understanding of first year ice pack characteristics and dynamics. Sophisticated studies have already been made that support the purely physical and mathematical approaches to the subject. Shipboard experience data is now needed to effectively integrate the presently fragmented knowledge to produce an effective modus operandi.

When one considers that the discovery of fossil fuel is likely, that there may be a strong desire to produce and transport fossil fuels throughout the winter months, and that a major marine terminal for ore is under construction, the increased knowledge of first year ice will be particularly useful to all persons affected by these activities. Those persons include oil spill contingency planners, environmentalists, search and rescue personnel, and a variety of scientists.

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APPENDIX A

SUNRISE AND SUNSET INFORMATION

Table A-1 indicates time of sunrise and sunset for the latitudes of the Bering Sea Atlas at longitude 165W.

Table A-2 provides time corrections for locations not on the standard meridian (165W).

Sunrise times can also be obtained from any relatively recent nautical almanac (Washington, 1983). Also given are times of civil twilight and nautical twilight. The process of deriving any of these times provides numerous opportunities for error. First, one must correct for latitude (Table A-1) as well as for distance from the nearest standard meridian (Table A-2). Then to be consistent with actual local time, one must correct to the actual meridian time designated for use in the area of interest. Alaska is unusual in that it uses Yukon Standard Time (135°W meridian) for the mainland of Alaska and most of the Bering sea atlas area. Thus, the time calculated from the tables will be two hours different than "mainland" time plus or minus the correction for distance to 165°W. During the summer, Alaska goes on daylight savings time which now requires a three hour correction from computed values.

The final complication is that the area west of St. Lawrence Island and west of the Pribilofs (approximately the western third of the atlas area) is in a different designated time zone, or one hour later than the Alaska mainland and eastern Bering Sea time. For operational purposes, it is probably adequate to assign one time zone to the atlas area, but that decision is left to the on-scene coordinator or others.

TABLE A-1 . -SUNRISE & SUNSET 1986

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Date		54° N		56° N		58° N		60° N		62° N		64° N	
		Rise	Set	Rise	Set	Rise	Set	Rise	Set	Rise	Set	Rise	Set
		h m	h m	h m	h m	h m	h m	h m	h m	h m	h m	h m	h m
Jan.	1	08 19	15 48	08 32	15 36	08 46	15 21	09 03	15 04	09 23	14 44	09 50	14 17
	6	08 18	15 54	08 29	15 42	08 43	15 29	08 59	15 13	09 19	14 53	09 44	14 28
	11	08 15	16 02	08 26	15 50	08 39	15 37	08 54	15 22	09 12	15 04	09 35	14 41
	16	08 10	16 10	08 21	15 59	08 33	15 47	08 47	15 33	09 04	15 16	09 24	14 56
	21	08 04	16 19	08 14	16 09	08 25	15 58	08 38	15 45	08 53	15 30	09 12	15 11
	26	07 58	16 28	08 07	16 19	08 17	16 09	08 28	15 57	08 42	15 44	08 58	15 27
	31	07 50	16 38	07 58	16 30	08 07	16 21	08 17	16 10	08 29	15 58	08 44	15 44
Feb.	5	07 41	16 48	07 48	16 41	07 56	16 33	08 05	16 24	08 16	16 13	08 29	16 01
	10	07 31	16 58	07 38	16 52	07 45	16 45	07 53	16 37	08 02	16 28	08 13	16 17
	15	07 21	17 08	07 26	17 03	07 33	16 57	07 39	16 50	07 47	16 42	07 56	16 33
	20	07 10	17 18	07 15	17 14	07 20	17 09	07 26	17 03	07 32	16 57	07 40	16 49
	25	06 59	17 28	07 03	17 25	07 07	17 21	07 12	17 16	07 17	17 11	07 23	17 05
Mar.	2	06 47	17 38	06 50	17 35	06 54	17 32	06 57	17 29	07 01	17 25	07 06	17 20
	7	06 36	17 48	06 38	17 46	06 40	17 44	06 42	17 41	06 45	17 39	06 46	17 35
	12	06 23	17 57	06 25	17 56	06 26	17 55	06 27	17 54	06 29	17 52	06 31	17 50
	17	06 11	18 07	06 12	18 07	06 12	18 06	06 12	18 06	06 13	18 06	06 13	18 05
	22	05 59	18 16	05 58	18 17	05 58	18 18	05 57	18 18	05 57	18 19	05 56	18 20
	27	05 47	18 26	05 45	18 27	05 44	18 29	05 42	18 31	05 40	18 33	05 38	18 35
April	1	05 34	18 35	05 32	18 37	05 30	18 40	05 27	18 43	05 24	18 46	05 20	18 49
	6	05 22	18 44	05 19	18 47	05 16	18 51	05 12	18 55	05 08	18 59	05 03	19 04
	11	05 10	18 54	05 06	18 58	05 02	19 02	04 57	19 07	04 51	19 13	04 45	19 19
	16	04 58	19 03	04 53	19 08	04 48	19 13	04 42	19 19	04 35	19 26	04 27	19 35
	21	04 47	19 12	04 41	19 18	04 35	19 25	04 27	19 32	04 19	19 40	04 10	19 50
	26	04 35	19 21	04 29	19 28	04 21	19 36	04 13	19 44	04 04	19 54	03 52	20 06
May	1	04 25	19 31	04 17	19 38	04 09	19 47	03 59	19 57	03 48	20 08	03 35	20 21
	6	04 15	19 40	04 06	19 48	03 57	19 58	03 46	20 09	03 33	20 22	03 18	20 37
	11	04 05	19 49	03 56	19 58	03 45	20 09	03 33	20 21	03 19	20 36	03 02	20 54
	16	03 56	19 57	03 46	20 08	03 35	20 19	03 21	20 33	03 05	20 50	02 45	21 10
	21	03 49	20 05	03 38	20 17	03 25	20 29	03 10	20 45	02 52	21 03	02 30	21 26
	26	03 42	20 13	03 30	20 25	03 16	20 39	03 00	20 55	02 40	21 15	02 15	21 41
	31	03 36	20 20	03 24	20 32	03 09	20 47	02 51	21 05	02 30	21 27	02 01	21 56
June	5	03 32	20 26	03 19	20 39	03 03	20 54	02 44	21 13	02 21	21 37	01 47	22 11
	10	03 29	20 30	03 15	20 44	02 59	21 00	02 39	21 20	02 14	21 45	01 38	22 22
	15	03 27	20 34	03 13	20 48	02 56	21 04	02 36	21 25	02 10	21 51	01 32	22 29
	20	03 27	20 36	03 13	20 50	02 56	21 07	02 35	21 27	02 09	21 54	01 31	22 32
	25	03 28	20 36	03 14	20 51	02 57	21 07	02 37	21 28	02 10	21 54	01 33	22 31
	30	03 31	20 36	03 17	20 50	03 00	21 06	02 40	21 26	02 15	21 51	01 40	22 26
July	5	03 35	20 33	03 21	20 47	03 05	21 03	02 46	21 22	02 22	21 46	01 50	22 17
	10	03 40	20 30	03 27	20 43	03 12	20 58	02 53	21 16	02 31	21 38	02 02	22 36
	15	03 46	20 25	03 34	20 37	03 20	20 51	03 02	21 08	02 41	21 29	02 16	21 53
	20	03 53	20 18	03 42	20 30	03 28	20 43	03 12	20 59	02 53	21 18	02 32	21 39
	25	04 01	20 11	03 50	20 22	03 38	20 34	03 23	20 48	03 06	21 05	02 44	21 26
	30	04 09	20 03	03 59	20 12	03 48	20 24	03 35	20 37	03 19	20 52	03 00	21 10
Aug.	4	04 17	19 54	04 08	20 03	03 58	20 12	03 46	20 24	03 32	20 38	03 '6	20 54
	9	04 26	19 44	04 18	19 52	04 09	20 01	03 58	20 11	03 46	20 23	03 31	20 37
	14	04 35	19 33	04 28	19 40	04 20	19 48	04 10	19 57	04 00	20 08	03 47	20 20
	19	04 44	19 22	04 38	19 28	04 30	19 35	04 22	19 43	04 13	19 52	04 02	20 03
	24	04 53	19 11	04 47	19 16	04 41	19 22	04 34	19 29	04 27	19 36	04 17	19 45
	29	05 02	18 59	04 57	19 03	04 52	19 08	04 46	19 14	04 40	19 20	04 32	19 28
Sept.	3	05 11	18 47	05 07	18 51	05 03	18 55	04 58	18 59	04 53	19 04	04 47	19 10
	8	05 20	18 35	05 17	18 38	05 14	18 41	05 10	18 44	05 06	18 48	05 01	18 52
	13	05 28	18 22	05 26	18 24	05 24	18 26	05 22	18 29	05 19	18 31	05 16	18 35
	18	05 37	18 10	05 36	18 11	05 35	18 12	05 33	18 14	05 32	18 15	05 30	18 17
	23	05 46	17 58	05 46	17 58	05 46	17 58	05 45	17 58	05 45	17 59	05 44	17 59
	28	05 55	17 45	05 56	17 45	05 56	17 44	05 57	17 43	05 58	17 42	05 58	17 41
Oct.	3	06 04	17 33	06 06	17 31	06 07	17 30	06 09	17 28	06 11	17 26	06 13	17 24
	8	06 14	17 21	06 16	17 18	06 18	17 16	06 21	17 13	06 24	17 10	06 27	17 06
	13	06 23	17 09	06 26	17 06	06 29	17 02	06 33	16 58	06 37	16 54	06 42	16 49
	18	06 33	16 57	06 36	16 53	06 41	16 49	06 45	16 44	06 51	16 38	06 57	16 32
	23	06 42	16 46	06 47	16 41	06 52	16 36	06 58	16 30	07 05	16 23	07 13	16 15
	28	06 52	16 35	06 57	16 29	07 04	16 23	07 11	16 16	07 19	16 08	07 28	15 58
Nov.	2	07 02	16 25	07 08	16 18	07 15	16 11	07 23	16 03	07 33	15 53	07 44	15 42
	7	07 11	16 15	07 19	16 08	07 27	16 00	07 36	15 50	07 47	15 39	08 00	15 26
	12	07 21	16 07	07 29	15 58	07 39	15 49	07 49	15 38	08 02	15 26	08 16	15 11
	17	07 31	15 59	07 40	15 50	07 50	15 39	08 02	15 27	08 16	15 13	08 32	14 57
	22	07 40	15 52	07 50	15 42	08 01	15 31	08 14	15 18	08 29	15 02	08 48	14 43
	27	07 49	15 46	07 59	15 36	08 11	15 23	08 26	15 09	08 43	14 52	09 03	14 31
Dec.	2	07 56	15 42	08 08	15 31	08 21	15 17	08 36	15 02	08 55	14 44	09 18	14 21
	7	08 03	15 39	08 15	15 27	08 29	15 13	08 45	14 57	09 05	14 37	09 30	14 12
	12	08 09	15 38	08 22	15 25	08 36	15 11	08 53	14 54	09 14	14 33	09 41	14 06
	17	08 14	15 38	08 27	15 25	08 41	15 10	08 59	14 53	09 20	14 32	09 48	14 03
	22	08 17	15 40	08 30	15 27	08 45	15 12	09 02	14 54	09 24	14 33	09 52	14 04
	27	08 19	15 43	08 32	15 30	08 46	15 16	09 04	14 58	09 25	14 37	09 53	14 09
Jan.	1	08 19	15 47	08 32	15 35	08 46	15 21	09 03	15 04	09 24	14 43	09 50	14 .6

Local mean time . To obtain standard time of rise or set , see table A2 (DOC , 1985)

TABLE A-2 . REDUCTION OF LOCAL MEAN TIME TO STANDARD TIME

Difference of longitude between local and standard meridian	Correction to local mean time to obtain standard time	Difference of longitude between local and standard meridian	Correction to local mean time to obtain standard time	Difference of longitude between local and standard meridian	Correction to local mean time to obtain standard time
° ′ ° ′	Minutes	° ′ ° ′	Minutes	°	Hours
0 00 to 0 07	0	7 23 to 7 37	30	15	1
0 08 to 0 22	1	7 38 to 7 52	31	30	2
0 23 to 0 37	2	7 53 to 8 07	32	45	3
0 38 to 0 52	3	8 08 to 8 22	33	60	4
0 53 to 1 07	4	8 23 to 8 37	34	75	5
1 08 to 1 22	5	8 38 to 8 52	35	90	6
1 23 to 1 37	6	8 53 to 9 07	36	105	7
1 38 to 1 52	7	9 08 to 9 22	37	120	8
1 53 to 2 07	8	9 23 to 9 37	38	135	9
2 08 to 2 22	9	9 38 to 9 52	39	150	10
2 23 to 2 37	10	9 53 to 10 07	40	165	11
2 38 to 2 52	11	10 08 to 10 22	41	180	12
2 53 to 3 07	12	10 23 to 10 37	42		
3 08 to 3 22	13	10 38 to 10 52	43		
3 23 to 3 37	14	10 53 to 11 07	44		
3 38 to 3 52	15	11 08 to 11 22	45		
3 53 to 4 07	16	11 23 to 11 37	46		
4 08 to 4 22	17	11 38 to 11 52	47		
4 23 to 4 37	18	11 53 to 12 07	48		
4 38 to 4 52	19	12 08 to 12 22	49		
4 53 to 5 07	20	12 23 to 12 37	50		
5 08 to 5 22	21	12 38 to 12 52	51		
5 23 to 5 37	22	12 53 to 13 07	52		
5 38 to 5 52	23	13 08 to 13 22	53		
5 53 to 6 07	24	13 23 to 13 37	54		
6 08 to 6 22	25	13 38 to 13 52	55		
6 23 to 6 37	26	13 53 to 14 07	56		
6 38 to 6 52	27	14 08 to 14 22	57		
6 53 to 7 07	28	14 23 to 14 37	58		
7 08 to 7 22	29	14 38 to 14 52	59		

If local meridian is east of standard meridian, subtract the correction from local time.

If local meridian is west of standard meridian, add the correction to local time.

For differences of longitude less than 15°, use the first part of the table. For greater differences use both parts thus: 47°23′ is equivalent to 45° + 2°23′, the correction for 45° is 3 hours, the correction for 2°23′ is 10 minutes; therefore the total correction for the difference in longitude 47°23′ is 3 hours and 10 minutes.

(DOC, 1985)

See text in Appendix A for correction to Local Designated Time .

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APPENDIX B

Storm Surge Forecast Procedures

I. Definitions

A. Surge - The height of the ocean's surface above forecast tidal levels.

B. Primary Surge - The surge that results directly from atmospheric winds.

C. Secondary Surge - The surge that results from gravity acting upon anomalous sea heights created by primary surges. See discussion in Section 6.7 of text.

D. True Wind Direction - The true direction from which the wind is blowing. A south wind is from 180°.

E. Relative Wind Direction - The direction from which the wind is blowing relative to the general direction of the coastline. For instance, if the coast is oriented SE to NW, the coast to the left, when facing the sea, is 000°; straight ahead (seaward) is 090°; and the coast to the right is 180°. Angles beyond 000° (counterclockwise) assume negative values. Thus an ESE wind relative to a SE - NW coast would be near -023°.

F. <u>Surge Wind Directions</u> - The sets of wind directions that are capable of producing primary surges. The surge wind directions for each sector are:

Surge Wind Directions

Sector	True	Relative
1	120 to 190	-017 to 053
2	195 to 250	035 to 090
3	190 to 280	-020 to 070

See Figure B-1 for sector locations. The above surge winds directions are merely estimations based on physical considerations of atmospheric and oceanic dynamics, the topographic effects of Nunivak Island, and case histories (Wise, et. al., 1981).

G. <u>Fetch</u> - An area in which wind direction and speed are reasonably constant and do not vary past the following limits:

(1) The wind direction or orientation of the isobars do not change direction at a rate greater than 15° per 180 nmi and the total changes do not exceed 30°.

(2) The wind speed does not vary more than 20 percent from the average wind speed in the area of the direction fetch being considered. Example: average wind is 40; acceptable range is 32 to 48.

H. <u>Fetch Duration</u> - The number of hours a coastal area is subjected to fetch winds.

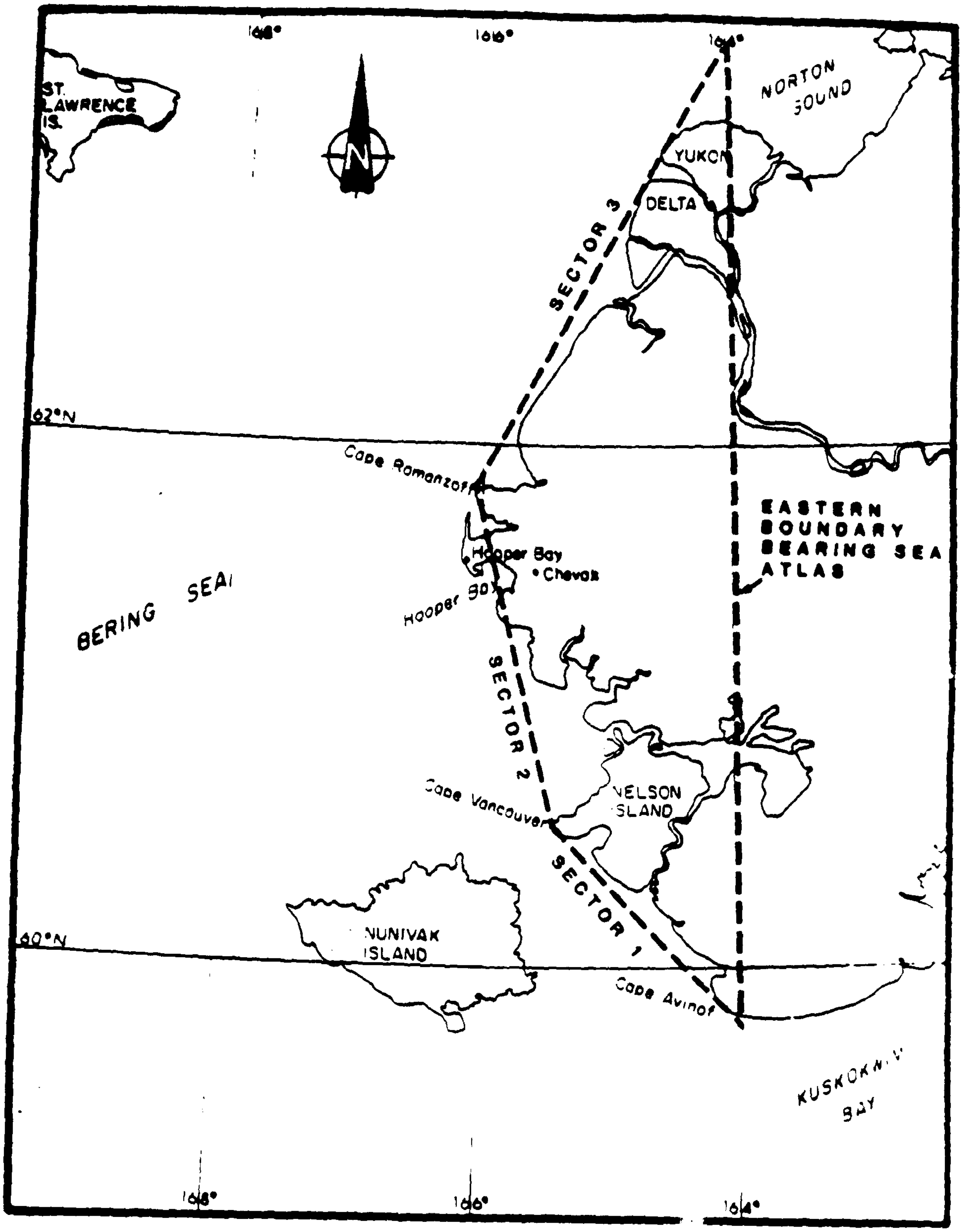

Figure B-1. Dashed lines indicate sectors and surge prone areas for selected sets of wind directions (surge winds). Sector directions are (1) 137-317°, (2) 159-339°, and (3) 208-028°.

I. <u>Lowest Pressure</u> - The lowest pressure coincident with fetch induced surge.

J. <u>Sea Ice Coverage</u> - (minimum expected during storm)- Percent of sea ice coverage in tenths.

K. <u>Sea Ice Character</u> - Primary concern is thickness and weakness. Thin or unconsolidated ice can be destroyed by storm action.

L. <u>Boundary Layer Stability</u> - The difference between the sea and air temperatures. The boundary layer temperature difference should be used when estimated the fetch wind speed from weather maps. The following guidelines are suggested:

Correction to Geostrophic Wind Speed for the Sea-Air Temperature Difference

$T_s - T_a$	Percent of Geostrophic Winds Used
0 or negative	60
0 to 10	65
10 to 20	75
20 or above	90

II. Procedures

A. <u>Determine</u>:

(1) Fetch wind (speed and relative direction). If direction is a surge wind direction continue with determination of:

(a) fetch duration

(b) ice cover and character

(c) lowest pressure

(d) tidal variation if over 1 foot

B. <u>Preliminary Surge Height</u> - Using wind speed, read correlated surge height from Figures B-2 or B-3.

C. <u>Duration Adjusted Surge Height</u> - If fetch duration is less than:

(1) 3 hours reduce surge by 60 percent

(2) 6 hours reduce surge by 40 percent

(3) 9 hours reduce surge by 20 percent

(4) 12 hours reduce surge by 10 percent

(5) 12+ hours no reduction

D. <u>Ice Cover Adjusted Surge Height</u> - If ice cover is less than:

(1) 1.5 tenths no reduction

(2) 3.0 tenths reduce surge by 20 percent (cumulative) to above)

(3) 5.0 tenths reduce surge by 50 percent (cumulative)

(4) 10.0 tenths reduce surge by 75 percent (cumulative)

E. <u>Pressure Adjusted Surge Height</u> - Raise the surge height one foot for every 30 mb pressure increment below 1004 mb.

F. <u>Tidal Adjusted Surge Height</u> - Check tide tables or other sources. If peak of surge is reasonably coincident with normal high water, make no correction. If surge misses normal high water, subtract as appropriate from surge height.

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APPENDIX C

Glossary of WMO Sea Ice Terms (WMO 1970)

The following ice nomenclature is abridged from a list adopted and published by the World Meteorological Organization (WMO, 1970).

Brash ice: Accumulations of *floating ice* made up of fragments not more than 2 m across, the wreckage of other forms of ice.

Compacting: Pieces of *floating ice* are said to be compacting when they are subjected to a converging motion, which increases ice *concentration* and/or produces stresses which may result in ice deformation.

Concentration: The ratio in tenths of the sea surface actually covered by ice to the total area of sea surface, both ice-covered and *ice-free*, at a specific location or over a defined area.

Diverging: *Ice fields or floes* in an area are subjected to diverging or dispersive motion, thus reducing ice *concentration* and/or relieving stresses in the ice.

Fast ice: *Sea ice* which forms and remains fast ag the coast, where it is attached to the shore. Vertical fluctuati... may be observed during changes of sea-level. Fast ice may be formed *in situ* from sea water or by freezing of *pack ice* of any age to the shore, and it may extend a few metres or several hundred kilmetres from the coast.

Finger rafting: Type of rafting whereby interlocking thrusts are formed, each floe thrusting "fingers" alternately over and under the other. Common in *nilas* and *gray ice*.

Firn: Old snow which has recrystallized into a dense material. 'Unlike snow, the particles are to some extent joined together; but, unlike ice, the air spaces in it still connect with each other.

First-year ice: *Sea ice* of not more than one winter's growth, developing from *young ice*; thickness 30 cm to 2 m. May be subdivided into *thin first-year ice*/white ice, *medium first-year ice* and *thick first-year ice*.

Flaw: A narrow separation zone between *pack ice* and *fast ice*, where the pieces of ice are in chaotic state; it forms when pack ice shears under the effect of a strong wind or current along the *fast ice boundary*.

Floe: Any relatively flat piece of *sea ice* 20 m or more across. Floes are subdivided according to horizontal extent as follows:
Giant: Over 10 km across.
Vast: 2-10 km across.
Big: 500-2,000 m across.
Medium: 100-500 m across.
Small: 20-100 m across.

Flooded ice: *Sea ice* which has been flooded by meltwater or river water and is heavily loaded by water and wet snow.

Ice boundary: The demarcation at any given time between *fast ice* and *pack ice* or between areas of *pack ice* of different *concentrations*.

Ice breccia: Ice pieces of different age frozen together.

Lead: Any *fracture* or passage-way through *sea ice* which is navigable by surface vessels. [Author's note: More typically taken to mean long linear opening of water between floes or groups of floes of 1 m to 100 m across and 100 m to a few kilometers long.]

New ice: A general term for recently formed ice which includes *frazil ice*, *grease ice*, *slush*, and *shuga*. These types of ice are composed of ice crystals which are only weakly frozen together (if at all) and have a definite form only while they are afloat.

Nilas: A thin elastic crust of ice, easily bending on waves and swell and under pressure, thrusting in a pattern of interlocking "fingers" (*finger rafting*). Has a matt surface and is up to 10 cm in thickness. May be subdivided into *dark nilas* and *light nilas*.

Open water: A large area of freely navigable water in which *sea ice* is present in *concentrations* of less than 1/10 (1/8). When there is no sea ice present, the area should be termed *ice-free*.

Pack ice: Term used in a wide sense to include any areas of sea ice, other than *fast ice*, no matter what form it takes or how it is disposed.

Polynya: Any non-linear shaped opening enclosed in ice. Polynya may contain *brash ice* and/or be covered with *new ice*, *nilas* or *young ice*. Sometimes a polynya is limited on one side by the coast and is called a *shore polynya* or by *fast ice* and is called a *flaw polynya*. If it recurs in the same position every year, it is called a *recurring polynya*.

Rafting: Pressure processes whereby one piece of ice overrides another. Most common in *new* and *young ice*.

Ridging: The pressure process by which *sea ice* is forced into *ridges*.

Sastrugi: Sharp irregular ridges formed on a snow surface by wind erosion and deposition.

Sea ice: Any form of ice found at sea which has originated from the freezing of sea water.

Shearing: An area of *pack ice* is subject to shear when the ice motion varies significantly in the direction normal to the motion, subjecting the ice to rotational forces. These forces may result in phenomena similar to a *flaw*.

Slush: Snow which is saturated and mixed with water on land or ice surfaces, or as a viscous floating mass in water after a heavy snowfall.

Snowdrift: An accumulation of wind-blown snow deposited in the lee of obstructions or heaped by wind eddies.

Young ice: Ice in the transition stage between *nilas* and *first-year ice*, 10-30 cm in thickness. May be subdivided into *gray ice* and *gray-white ice*.

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